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Designing and Testing a Relative Resiliency Framework for Groundwater Management

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Designing and Testing a Relative Resiliency Framework for Groundwater Management

by

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Dedication

I dedicate this work to my best friend Max. As a dog he may not understand the contents of this thesis but his patience and positive attitude through the long hours of writing has been appreciated.

Acknowledgements

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Abstract

Designing and Testing a Relative Resilience Framework for Groundwater Management

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The University of Texas at Austin, 2017

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Groundwater enables economic growth, agriculture, and human expansion into areas that would otherwise not support large populations due to the water supply resilience. Underground aquifers and springs can provide water to regions and communities which overlie them. The groundwater resources of Texas have so far proven to be relatively resilient in most areas despite considerable pumping, anticipated population growth, climate change, and the threat of drought which may amplify the vulnerability of these resources. During the next 50 years, the population of Texas is expected to increase significantly, with the majority of growth expected in the municipal sector. Texas' Water Plan, as published every five years by the Texas Water Development Board (TWDB) in conjunction with Regional Water Planning Groups, aids the policy making process to meet demands for surface and groundwater resources.

This research presents a relative resilience framework that incorporates multiple dimensions of resilience and vulnerability using spatial and temporal variables to assess regional water supply resilience on a relative scale. The framework is tested with an

analysis of counties along the Interstate-35 corridor. Given the relative nature of the variables and the scales upon which they are measured, the framework becomes stronger and more accurate as additional data are added. Through this framework, a region's relative water supply resilience against other regions can be measured and visually represented. The relative measurement scale, which this framework is built on, was tested with county-level data to depict the relationships among regions. The framework is scalable and multi-dimensional. It can be adapted for use in other settings, it facilitates discussion of resilience components that affect groundwater resources and the regions they serve.

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Chapter 1: Introduction

Communities that depend on water resources can face stress from population growth, climate change, and the threat of drought. Texas' population in 2017 stands at 28,797,290 and state demographers anticipate an increase of 77.2% by 2070 (TDSHS, 2017) (TWDB, 2016). This growth holds the potential to strain the Texas' water resources despite the abundance of aquifers in the State.

The 2017 Texas State Water Plan estimates annual state groundwater availability will be 12.3 million acre-feet in 2020 (TWDB, 2016). Despite this abundance, Texas has actually experienced a net loss of water from groundwater sources due to over-pumping in certain areas of the State (George et al., 2011). Water contamination can also reduce availability regardless of the actual quantity that is accessible.

Water availability, demand, and planning vary by countries, states, and even regions. This research develops a relative resiliency framework, which for simplicity will be referred to as the RRF. The RRF is an approach to constructing scalable and modifiable multi-attribute performance measures. A framework is a conceptual tool which allows for numerous related factors to be analyzed in a holistic manner. Such a framework can be applied to numerous issues to identify relevant variables, their relationships, and to observe how minor changes in specific variables can affect the system. This thesis implements an initial test to demonstrate the RRF, to illustrate groundwater supply resilience for a region in Texas. By testing the framework on population centers in Texas, it will be possible to scale and expand its potential applicability to other localities.

Definitions

Resilience and vulnerability are defined in numerous ways throughout previous research. Hashimoto et al., (1982) put forth the concept of quantifying the resilience of water resource systems through the gauging of water supply reservoirs. Peters et al., (2004) defined resilience as how quickly a system is likely to recover once a failure has occurred, while vulnerability is the severity of the failure. Sharma and Sharma, (2006) defined groundwater resilience as the ‘‘ability of the system to maintain groundwater reserves in spite of major disturbances.’’ Hugman et al., (2012) identified the hydraulic properties of an aquifer, such as transmissivity and storage capacity, as indicative of its resilience, particularly during extreme climate events such as droughts. Ritchey et al., (2015) defined groundwater availability as the total volume of groundwater in storage which allows for the concepts of groundwater resiliency and buffer capacity to be explored. The Action Research for Community Adaptation in Bangladesh (ARCAB) framework uses the following definition of resilience:

> *The achievement of long term development in spite of, or in light of, climate change. – (Dodman et al., 2009)*

Several studies state a groundwater system’s resilience will fail at the point in which discharge overwhelms recharge over the time period of concern (Theis, 1940; Alley et al., 2002; Alley and Leake, 2004). This definition leads to the concept of vulnerability.

Vulnerability has been defined in many ways, for example, some researchers defined vulnerability as the “average drought deficit” (Vaz, 1986; Loucks, 1997; Kjeldsen and

Rosbjerg, 2001). Others define it as the "maximum drought" (Moy et al., 1986). The ARCAB framework derives its definition of vulnerability from Wisner et al., (2004):

> *The state that determines the ability of individuals or social groups to respond to, recover from, or adapt to, the external stresses placed on their livelihoods and well-being by climate hazard. – (Wisner et al., 2004)*

In this definition and its overall framework, the ARCAB framework blends the definition of resiliency into vulnerability. The "Household Vulnerability Framework" developed by Richmond, et al., (2015) defines vulnerability as:

> *The inability to withstand the effects of social or environmental changes. – (Richmond et al., 2015)*

In this definition and the variables of this framework, a focus is placed on the impacts of environmental changes on households and communities. All of these definitions relate to groundwater's susceptibility to change and correspond with the general definition of vulnerability (Merriam-Webster, 2016).

Another concept is "sustainable yield," which is related to aquifer yield. While aquifer yield generally accounted for groundwater by what was economically recoverable, sustainable yield accounted for:

> *"Recharge rates and storage conditions; water quality; discharge rates and environmental flows; legal constraints; economic feasibility; and issues of inter-generational equity." (Pierce et al., 2013; Zhou, 2009; Devlin and Sophocleous, 2005; Kalf and Wooley 2005; Alley and Leake 2004;*

Sophocleous 2000; Alley et al. 1999; Domenico, 1972; Todd, 1959; Kazmann, 1968, 1956; Thomas, 1951; Conkling, 1945).

Adaptive capacity is a dimension in some resilience frameworks. For example, the Department of International Development (DFID) defines "adaptive capacity" as:

> *The factors that specifically enable people to anticipate, plan for and respond to changes (for example by modifying or changing current practices and investing in new livelihood strategies). - (DFID, 2014)*

The ARCAB framework also asserts the dependence of resilience on adaptive capacity which it defines as:

> *The ability to adjust to change, moderate damage, take opportunities and respond to consequences. - (ARCAB, 2012)*

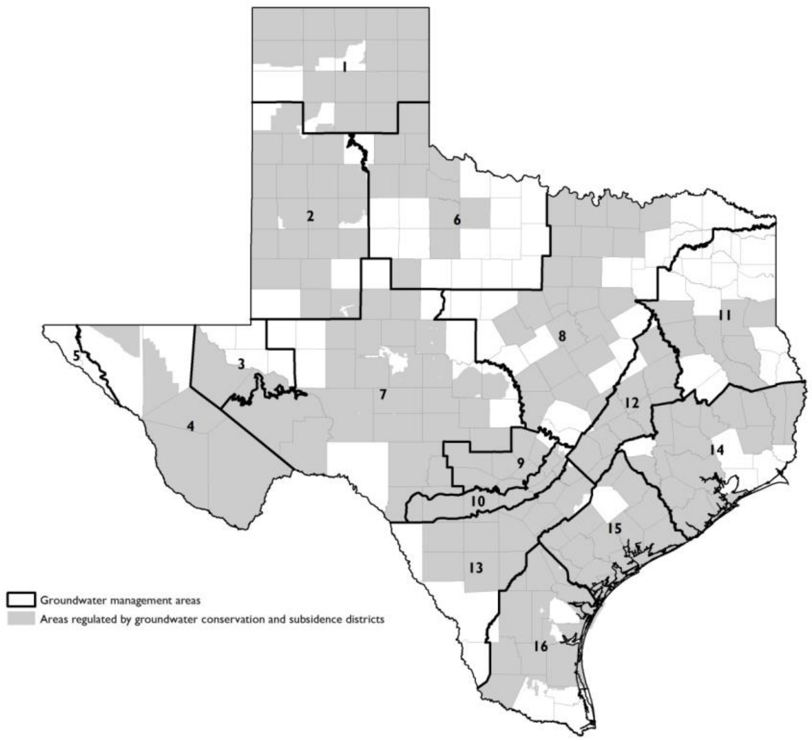
Adaptive capacity can be applicable to other dimensions of personal and community resiliency which range from assets, access to services, as well as income and food access (DFID, 2014). This definition refers to a person or community's ability to adapt to climate change, which affects their access to natural resources such as water (DFID, 2014). These definitions of resilience, vulnerability, and adaptive capacity form the basis of three types of so-called "frameworks": community resilience frameworks; groundwater analysis frameworks; and groundwater resilience frameworks (see Appendix 1). For the purposes of the Relative Resilience Framework, vulnerability and resilience will be placed on opposing ends of the scale as antonyms of each other. Therefore, vulnerability will be defined as "the susceptibility of the region to water shortages" and resilience is defined as "a region's strength against water shortages."

Background and History of Groundwater in Texas

The rate at which Texas residents pump groundwater substantially increased in the 1950's during the drought of record. Prior to this event, Texans pumped 2 million acre-ft of groundwater per year. Pumping jumped to 10 million acre-ft per year during the 1950's (George et al., 2011). Pumping rates have not returned to previous levels since the 1950's. Groundwater has allowed Texans to settle and even conduct large-scale agriculture in areas that were otherwise not conducive to such activities. The "Winter Garden" region supports year-round agriculture with water out of the Southern portion of the Carrizo-Wilcox Aquifer (George et al., 2011). The Ogallala Aquifer has made large-scale agriculture possible in the otherwise arid Panhandle of Texas. These aquifers contribute to the water supply resilience of their respective areas.

Population growth presents a multitude of challenges, including how to fulfill water needs of people without placing an inordinate strain on Texas' natural resources. Currently, Texas manages its water resources through the Texas Commission on Environmental Quality (TCEQ) and the Texas Water Development Board (TWDB) (Legislative Library of Texas, 2016). Groundwater in Texas is subject to the "rule of capture," which allows landowners the right to capture water flowing beneath their property (Legislative Library of Texas. 2016). The TWDB has divided Texas into Groundwater Management Areas (GMA) and the Groundwater Conservation Districts (GCD) contained within the GMA's (TWDB, 2014). GMA's and their respective GCD's take part in a joint planning process in which the districts utilize modeled available groundwater and issue pumping permits which can meet desired future conditions (DFC). Figure 1-1 illustrates the boundaries and jurisdictions of GMA's and GCD's. Some GMA's follow the boundaries of aquifers. Some GCD's are drawn along county lines. There are also areas without GMA's or GCD's (McPherson, 2008).

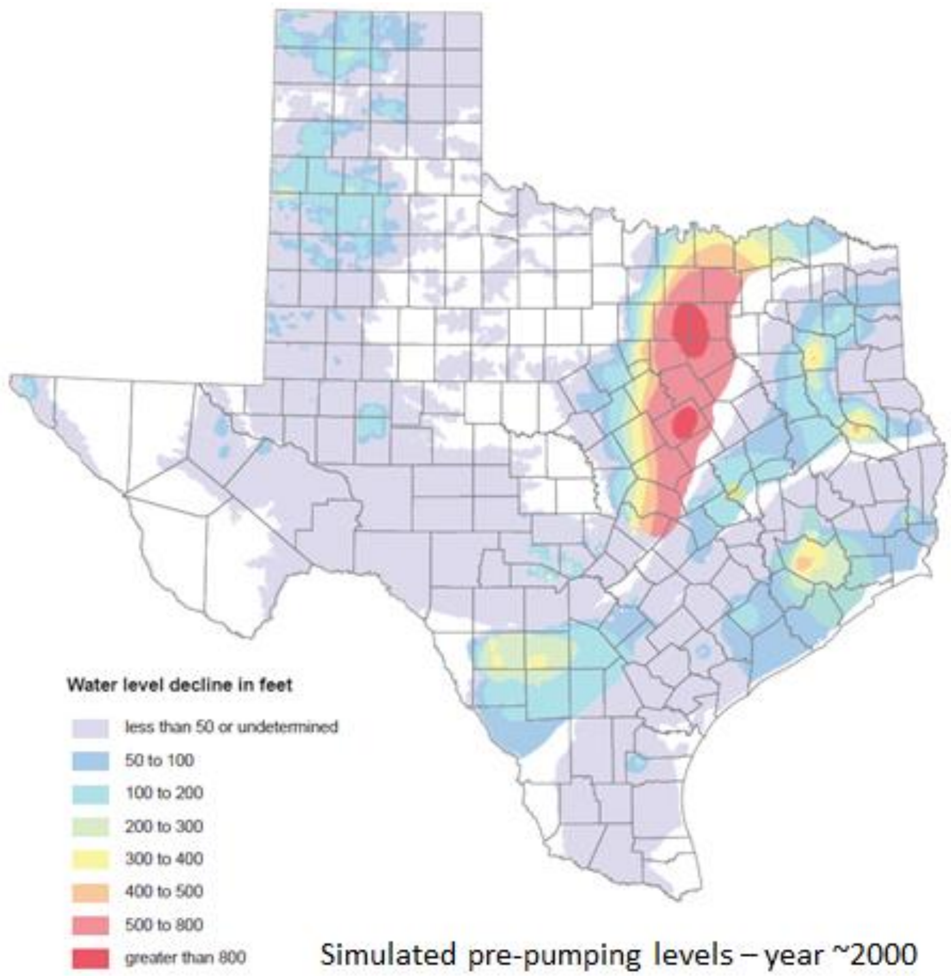
Figure 1.1: Groundwater Management Areas, Groundwater Conservation Districts, and Subsidence Districts



Source: Texas Water Development Board, 2016. Water for Texas, 2017 State Water Plan.

Groundwater supplies are influenced by the geology of the underlying aquifer. Aquifers can be vulnerable to over-pumping; in times of heavy demand, aquifers may not be able to sustainably supply the demand without declines in water levels (Scanlon, 2002). For example, the TWDB in 2011 reported aquifer level declines along the I-35 corridor, especially in the Trinity Aquifer under the Dallas, Fort Worth, and Waco area (Fig. 1.2) (George et al., 2011).

Figure 1.2: Estimated Groundwater Declines since Pre-Pumping Levels



Source: George, et al., 2011. Aquifers of Texas: Texas Water Development Board, Numbered Reports, Report 380.

The Carrizo-Wilcox has also experienced aquifer declines, particularly in the Winter Garden Region (George et al., 2011).

Water planning in Texas utilizes the drought of record, either from the 1950's or the more recent 2010's, as a baseline (TWDB, 2016). As resiliency data is drawn from regional water plans and the Texas State Water Plan, this drought record assumption is carried into the resiliency framework. However, tree ring records indicate that droughts even longer than the 1950's drought of record have occurred in this region's history as recently as the 16th century (Cleaveland et al., 2011). Droughts seem to be relatively unpredictable. It is difficult to justify planning for a worst case scenario which has not occurred. The task of incorporating unknown and uncertain future conditions becomes challenging as increased mitigation measures could affect economic interests negatively.

> *"While Texas has recently emerged from its second-worst statewide drought, we do not know when the next drought will occur." – (TWDB, 2016)*

The drought which began in 2010 set drought of record conditions in some parts of Texas and in those areas became the new baseline for water planning (TWDB, 2016). Data indicate that most of Texas has experienced increasing average precipitation rates over the last century and extreme precipitation events are on the rise (Fig. 1.3a & 1.3b). These extreme precipitation events cause the average precipitation rates to rise and skew the average to be misleading in terms of typical precipitation rates. This is especially problematic when considering the slow recharge rates of many aquifers. Extreme precipitation events may lead to floods and runoff, and may not contribute so significantly to groundwater recharge.

Figure 1.3a: Extreme one-day precipitation events in the contiguous 48 states 1910-2015

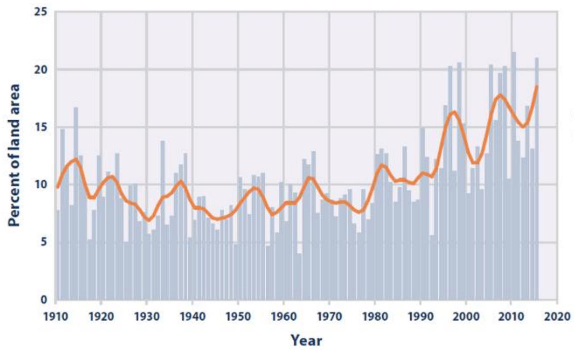
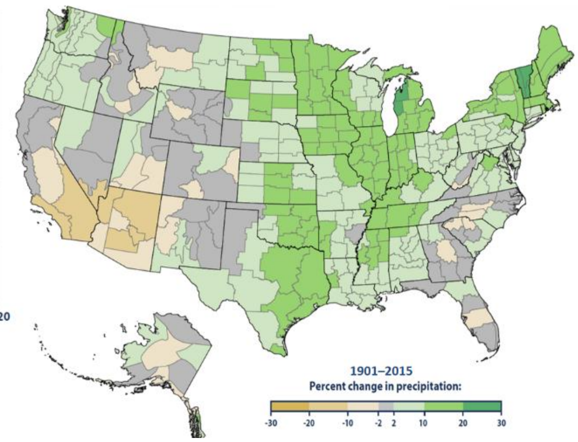


Figure 1.3b: Changing rates of annual precipitation (since 1901 for the contiguous 48 states and 1925 for Alaska)



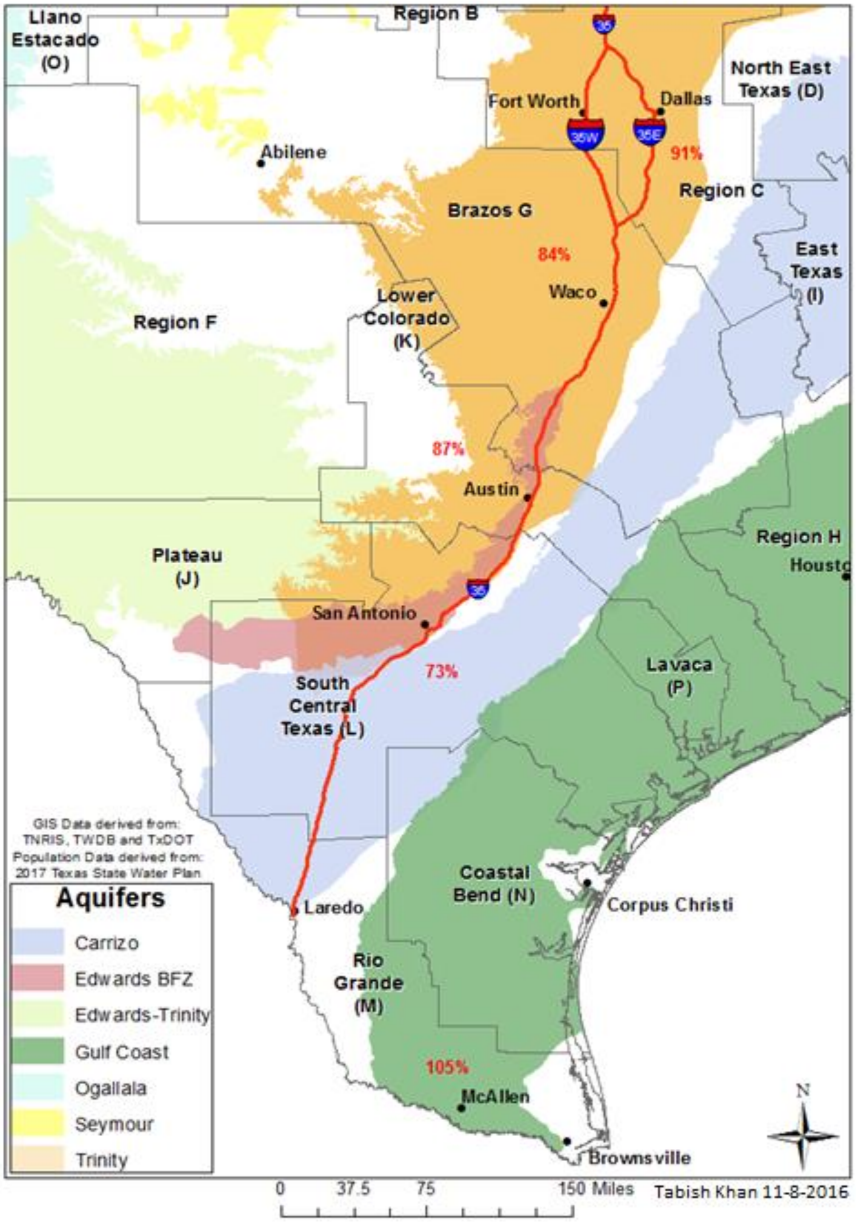
Source: “Climate Change Indicators in the United States”, Fourth Edition. (Environmental Protection Agency, 2016. Web, Nov 2016).

Scope of Research

The study area used to develop and populate the RRF framework is limited to Texas’ I-35 corridor which includes several large municipalities within Regional Water Planning Areas C, G, K, L, and M. These regions are projected to receive the highest percentages of growth in Texas from 2020 – 2070 (Table 1-1) (Fig 1.4) (TWDB, 2016). These projections are based on the expectation that there will be a strong trend towards urbanization during this planning period (TWDB, 2016). Region M, in South Texas where the City of McAllen and Brownsville are located, is expecting the highest rate of growth in all of Texas (Table 1.1; TWDB, 2016).

Figure 1.4

Major Aquifers and Predicted Population Growth of Central Texas RWPAs from 2020-2070



GIS layers derived from the Texas Natural Resources Information System, the Texas Water Development Board, and the Texas Department of Transportation.
Population growth data derived from 2017 Texas State Water Plan.

Chapter 2: Literature Review

Introduction to Resilience and Frameworks

Since 2011, resource analysts have produced notable resilience research on topics such as climate change, community health, food security, and disaster relief (Table 2.2) (Schipper and Langston, 2015). Some of this research has been led by humanitarian organizations or non-government organizations (NGO) dedicated to international aid, reflecting the dependence of humans and ecosystems upon this resource (Schipper and Langston, 2015) (Steward et al., 2009). One theme is achieving inter-generational equity to ensure groundwater availability for future use, balancing natural and man-made discharge with recharge, through natural discharge factors such as evapotranspiration and subsurface flows (Ritchey et al., 2015). Groundwater aquifers may be affected by climate change and pumping by humans (Ritchey et al., 2015). Some studies conducted by the EPA and others have reported shifts in the seasonal distribution and yearly variability of rainfall, and therefore recharge, can be expected in the second half of the 21st century (EPA, 2016; Stigter et al., 2011). Seasonal rainfall may increase during the winter at the expense of lower rainfall in the spring and autumn months (Stigter et al., 2011). Stigter et al., (2011), hypothesize that inter-annually, extreme rainfall events, and ever-longer droughts may become more common. Hugman et al., (2012) reported that concentrated rainfall from climate change could reduce sustainable aquifer yields by 3-5% over time, based on similar examples of public supply withdrawals (A), aquifer storage coefficients, and locations of public supply wells with the distribution of recharge being the test variable (Table 2-1) (Hugman et al., 2012). The distribution of recharge variables tested two scenarios – average annual value of recharge distributed uniformly over six months from October to March against average annual value of recharge distributed two months from November to December (Hugman et al., 2012). The first scenario depicted standard present day conditions while the second scenario simulated an extreme version of changes in rainfall patterns as a result of climate change (Hugman et al., 2012). Appendix 1 lists additional community and groundwater resilience frameworks.

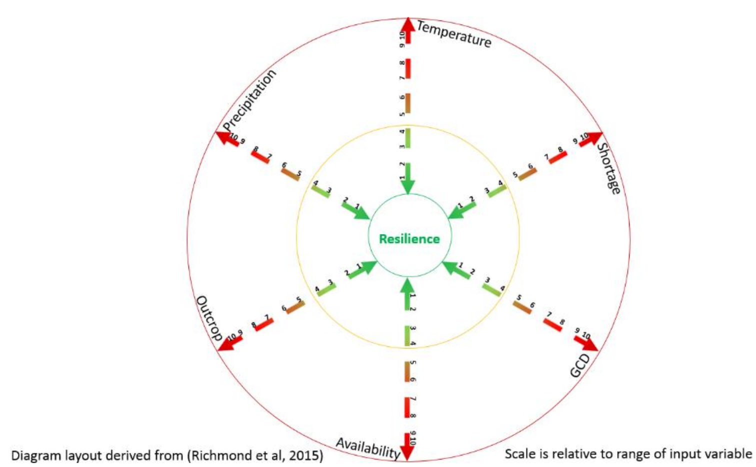
Chapter 3: Introduction to the RRF

This report develops a categorical approach to organize multi-attribute variables to provide a concise, graphical means to evaluate difficult problems on a resilience to vulnerability scale. This approach is scalable and repeatable in other scenarios with varying data. The goal of this framework is to provide a visual and holistic view of an area's relative resilience against extreme or chronic events which threaten water supplies.

Summary of Methodology

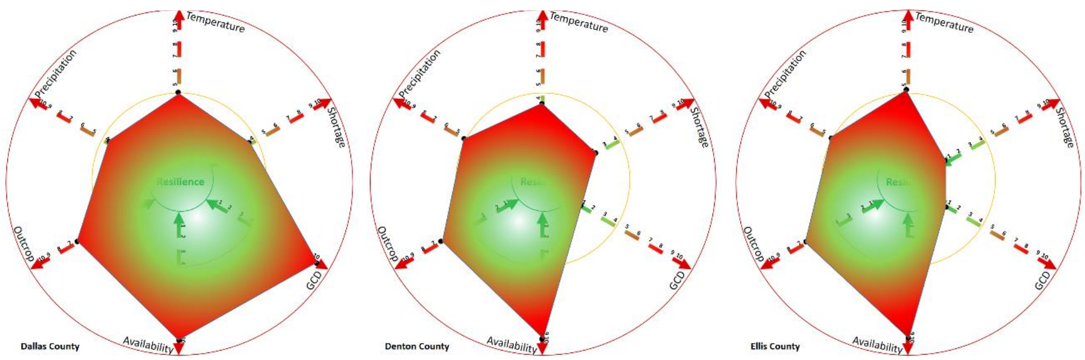
To build a tool to visualize multiple metrics that are used to evaluate groundwater resilience: indicators of groundwater resilience were chosen; a metric was selected to represent the indicator; data were identified to measure the metric and tabulated (Appendix 2); the data were normalized to fit the scale by converting their real values to representative values on a scale of 0-10 with "0" indicating high resilience and "10" indicating high vulnerability (Appendix 2); and the scale values were plotted on the radial spoke representing their indicator on the RRF diagram (Figure 3.1).

Figure 3.1: RRF Diagram



After plotting the scaled values for a particular subject located within the study area, a polygon can then be drawn by connecting the dots and this will give a visualization of the subject's relative resilience categorically and overall to other subjects in the dataset (Figure 3.2).

Figure 3.2 RRF Results Sample



The study area chosen for this proof of concept was the I-35 corridor in Texas. This region was divided by individual counties for which data were collected. Six key indicators were chosen and they are representative concepts that reflect resilience:

Average annual high temperature – These data were collected from "U.S. Climate Data" online and indicate the average high temperature of a city located within the county for all months in a year (Table 3-2) (USCD, 2016). The temporal range of this average is provided on a city by city basis in Table 3-2. The city acts as a proximate representative of the county's annual average high temperature.

Average total annual precipitation – These data were collected from "U.S. Climate Data" online and indicate the average total inches per year of rain that a city within the county receives (Table 3-2) (USCD, 2016). The temporal range of this average is provided on a city by city basis in Table 3-2. The city acts as a proximate representative of the county's annual average high temperature.

Estimated total groundwater availability of the region's underlying aquifer – These data were collected from the 2007 TWDB State Water Plan and indicate the estimated groundwater availability of the entire aquifer the county is in the territory of in acre-ft per year for 2010 (Table 3-3) (TWDB, 2007).

Total area of the outcrop of the aquifer underlying the region – These data were collected from the 2007 TWDB State Water Plan and indicate the area of the whole outcrop associated with the aquifer the county is in the territory of in square miles (Table 3-3) (TWDB, 2007).

The existence of a GCD in the region – This metric was based on a simple analysis of whether or not the county being measured was located in the territory of a GCD or a Subsidence District which would indicate permitting of groundwater withdrawals. This is a metric which needs more development as there is more nuance to the factors which go into how effective groundwater management is at the local level (Figure 3.3).

Shortage – These data were collected from the 2016 Regional Water Plans for Regions B, C, G, K, L, M, and N. The data indicate the difference between total expected supply and total expected demand in acre-ft. per year for each county by 2040 if water management strategies are not executed (Table 3-1).

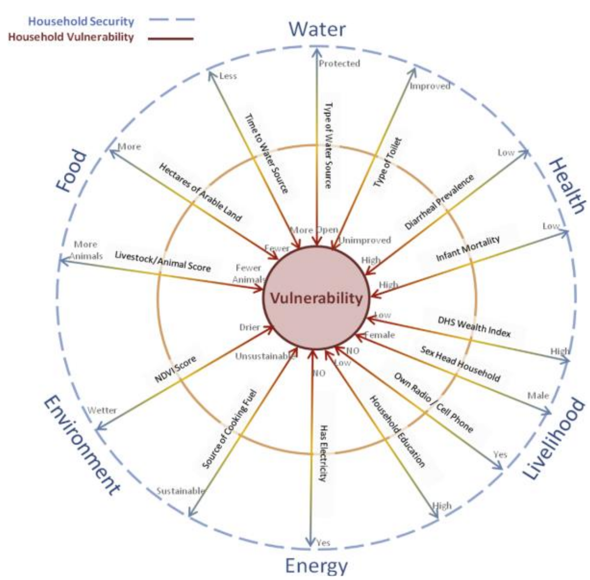
Indicator Selection

Indicators are measurable metrics which are synonymous with what Keeney and Gregory, (2005) refer to as "attributes." Keeney states that attributes need to be unambiguous, comprehensive, direct, operational, and understandable (Keeney and Gregory, 2005). These attribute characteristics build on Keeney's research organizing attributes into three categories: natural attributes, constructed attributes, and proxy attributes. Natural attributes are related directly to the observation; they are the simplest to measure and the easiest to portray (Keeney, 1992). For example, to describe the amount of water drained from a container, a volumetric measurement of the water before and after the container is drained would provide an exact value of how much water was lost from the container. Natural attributes are the preferred category of attributes (Keeney and Gregory, 2005). Constructed attributes allow for observations and measurement of a topic where no real natural attribute exists – such as the stock market (Keeney and Gregory, 2005). The Dow Jones index was a constructed attribute derived from a collection of stock scores to indicate the general trend of the stock market (Keeney and Gregory, 2005). Proxy attributes do not measure the objective of concern directly; through a relationship with the performance variable they provide an indication of the sought-after metric. For example, the quality of a restaurant may be measured by the number of repeat customers. This is not a direct indication of the quality of the restaurant. However, it does provide a measure by which to gauge quality despite many other variables which may also effect the result.

RRF Derivation and Framework Design

Variables from resilience frameworks listed in Appendix 1 were evaluated and included in the RRF if they indicated regional water supply resilience and the required data was accessible. This test of the RRF measures four categories which are divided into six variables. The categories include: formation, which consists of outcrop area and groundwater availability; policy, which accounts for the existence of a GCD in the region; supply and demand, which is combined into the shortage variable; and climate, which takes into account average annual high temperatures and average annual precipitation (Table 3-1, Table 3-2, Table 3-3). These variables were analyzed against the qualifications for desirable attributes given by Keeney and Gregory, (2005), to provide further validation. The following diagram developed by Richmond, et al., (2015) was the design source for the RRF Diagram (Fig. 3.1).

Figure 3.1: Household Vulnerability Network Model



Source: Richmond et al., 2015. Household Vulnerability Mapping in Africa's Rift Valley: Applied Geography, no. 63, p. 380–395.

Proportional Metrics

The RRF presents each variable or measure for a specific region under study as a proportional metric. Each proportional metric is measured only against the range of data within its variable type, which indicates its relative resilience to the other data. As additional sets of variables are added, the maximum and minimum values can change which would adjust the proportional values of every case study to the new range. Therefore, each metric is plotted proportionally with respect to the maximum and minimum values present in the dataset. For example: the availability of aquifer A is 10 acre-ft; aquifer B is 100 acre-ft; and aquifer C is 55 acre-ft. The maximum availability is set at 100 acre-ft and the minimum will be 10 acre-ft. Therefore aquifer A will be represented with a scale value of 10 – highly vulnerable and aquifer B will be represented with a scale value of 0 – highly resilient. Aquifer C in this example falls directly in the middle of the range and therefore receives a scaled value of 5.

Category Descriptions and Variables

Based on an evaluation of available data with guidance from previous research, the following categories were selected in order to construct the proof-of-concept RRF.

- Supply and Demand
- Policy
- Climate
- Formation

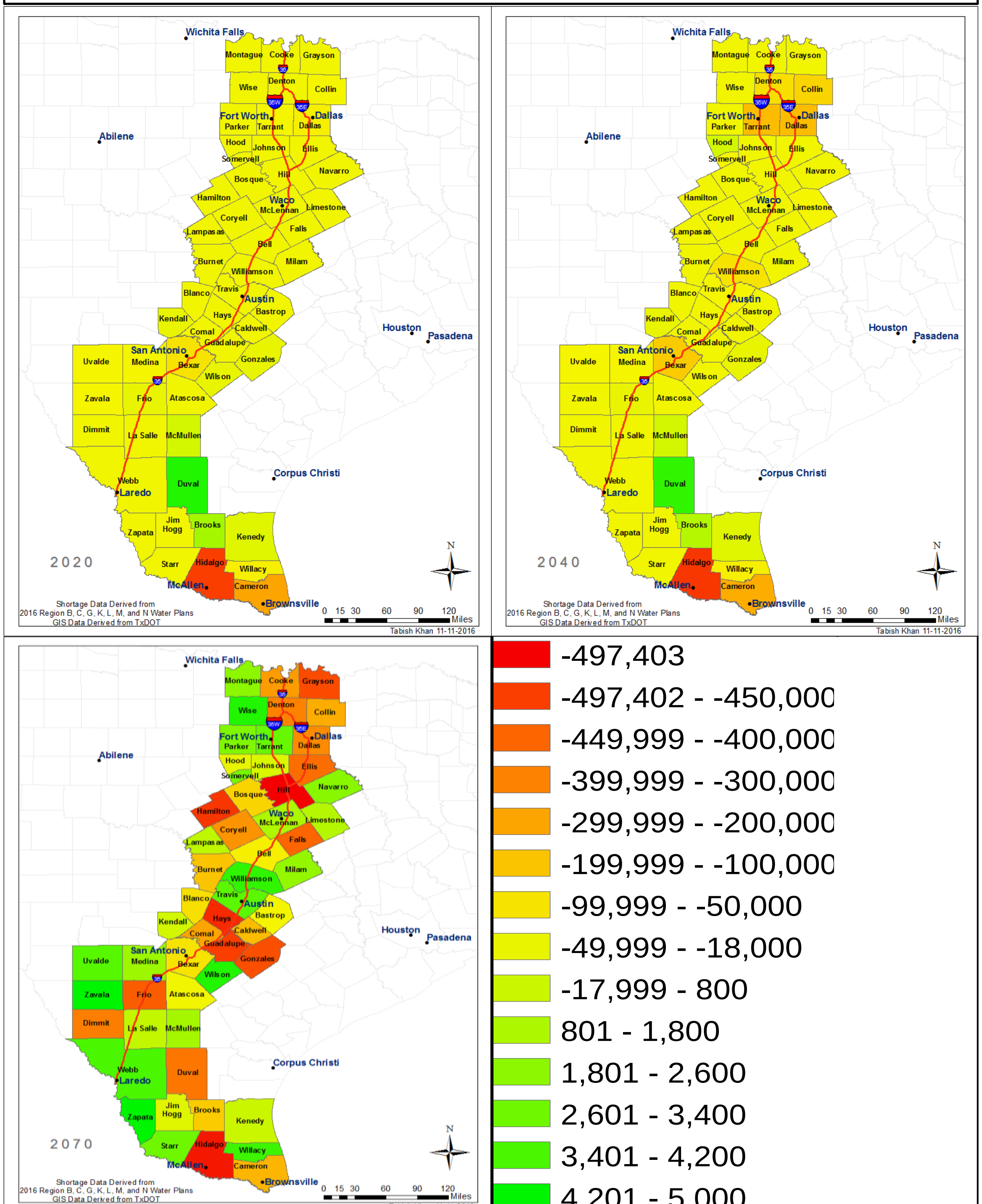
Each category is then subdivided into the variables for which raw data was gathered and converted into the scaled values for display.

Supply and Demand

<u>Supply and Demand:</u> The supply and demand data was obtained from the Texas Regional Water Plans. Shortages can be calculated from this data by comparing projected supply from all water sources against projected demand from all water users groups for the planning period – which is 50 years. The data range for shortages included all values in a given planning year for the counties within the study area outlined in Figure 3.2. The following measure is used for the proof of concept implementation in the Supply and Demand Category:

- Shortages - measured in acre-feet/year by county within the study area (Table 3.1, Fig 3.1).

Figure 3.2: Shortages by County (Acre-Feet/Year)



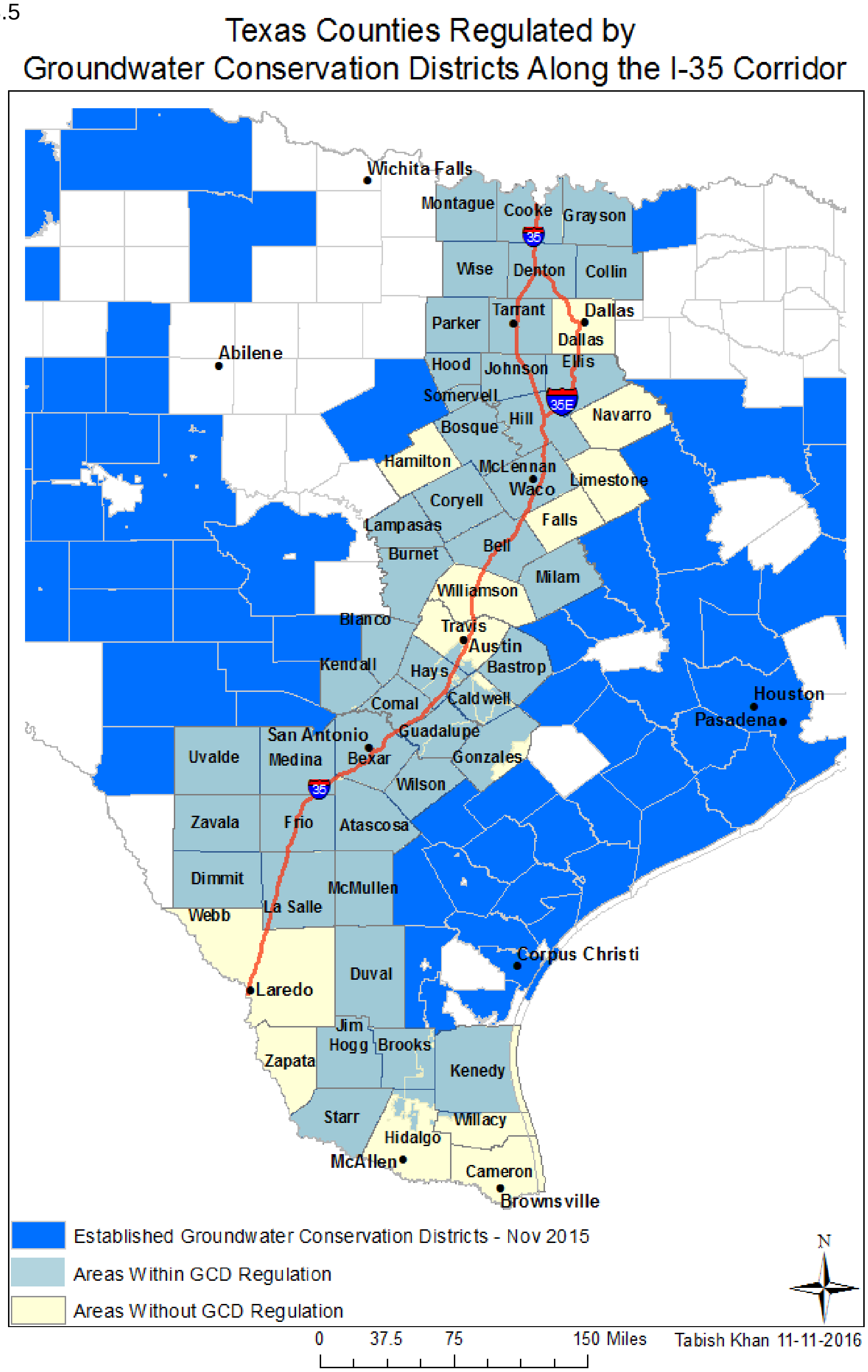
GIS layers derived from the Texas Department of Transportation.
Shortage data derived from 2016 Region B, C, G, K, L, M, and N water plans.

Public Policy

Public Policy: GCD jurisdiction over a county allows permitting based on the desired future conditions developed from modeled available groundwater. This measure can indicate enhanced resilience, however, is not readily quantifiable and can be inconsistent. As a constructed attribute, a value system must be assigned to quantify this variable. This category can benefit from additional variables such as the strength of GMA cooperation, compliance with permitting, and consistent rules between GCDs. Most counties have GCDs which span their political boundaries while others may be conglomerates of multiple counties (Fig 3.3). In addition, some counties such as Hidalgo, have partial GCD coverage. The following measures are used in the Public Policy Category:

- The presence of a GCD will yield a scale value of "1" or highly resilient.
- The absence of a GCD will yield a scale value of "10" or highly vulnerable.
- Partial jurisdiction within the county will yield a scale value of "5" or moderately resilient.

Figure 3.5



GIS layers derived from the Texas Department of Transportation and the Texas Water Development Board.

Climate

Climate: The climate of a region can affect groundwater recharge, surface water stability, and regional dependence on water resources. The effects of climate on different regions can be unique and dependent on many variables. However, variables which offer a reliable and consistent indicator of climactic influence on a particular area were necessary. Data for the climate category was derived from U.S. Climate Data online and records range between 1981-2010 as well as 1961-1990 (Table 3.2; USCD, 2016). The following measures are used in the Climate Category:

- Historical record of annual precipitation rates – collected by city to indicate proximate value for surrounding county and measured in average inches per year.
- Historical annual average high temperatures – collected by city to indicate proximate value for surrounding county and measured in degrees Fahrenheit.

Formation

Formation: The formation category contains variables which indicate the region's access to resilient groundwater sources. Groundwater provides a diversification factor to a region's water supply which reduces susceptibility to water shortages during drought. The variables which contribute to an aquifer's resilience must then be evaluated to gain resolution on the aquifer's contribution to regional resilience. Data for the formation category were extracted from the 2007 "Water for Texas" State Water Plan (Table 3.3) (TWDB, 2007). The availability data range reflects a range provided in the "Individual Aquifer Data" section of the modeled groundwater availability for 2010. Outcrop surface area is also derived from the "Individual Aquifer Data" section of the 2007 State Water

Plan (TWDB, 2007). The outcrop and availability range contains the data of all major and minor aquifers which are located in, or go through, the State of Texas. The following measures are used for the proof of concept implementation in the formation category:

- Groundwater availability of the entire aquifer atop which the county is located – measured in acre-feet.
- Area of the entire outcrop of the aquifer atop which the county is located – measured in $miles^2$.

Quantitative Evaluation

Compilation of the data and normalization to a 1-10 scale allowed for relative measurement of resilience by variable for each county. The following equation (Eq. 1) allowed for each real value to be proportionally measured on a scale of 1-10 within the range of the input dataset. The resulting "V" value can then be plotted on its respective radial line on the circular diagram. To calculate "V", the following equation was used where:

- X = The real world value of the specific variable (i.e. area of outcrop).
- X_{Max} = The maximum value in the range of real values for the specific variable.
- X_{Min} = The minimum value in the range of real values for the specific variable.
- $X_{Max} - X_{Min}$ = The range of the dataset.

Therefore, the following equation provides the position of a real value on a scale of 1-10 in relation to its dataset.

Equation 1: Real Value to Scale Value Conversion

$$X = Real\ Value\ of\ Variable$$

$$\frac{10(X_{Max} - X)}{X_{Max} - X_{Min}} = Scaled\ Value\ (V)$$

All variables, except for temperature, equated to higher resilience with larger real world values. Due to higher real world temperatures yielding lower resilience, the "V" value of the temperature variable was subtracted from 10. This inverted its location on the radial scale to follow the same direction indicating resilience as the other values.

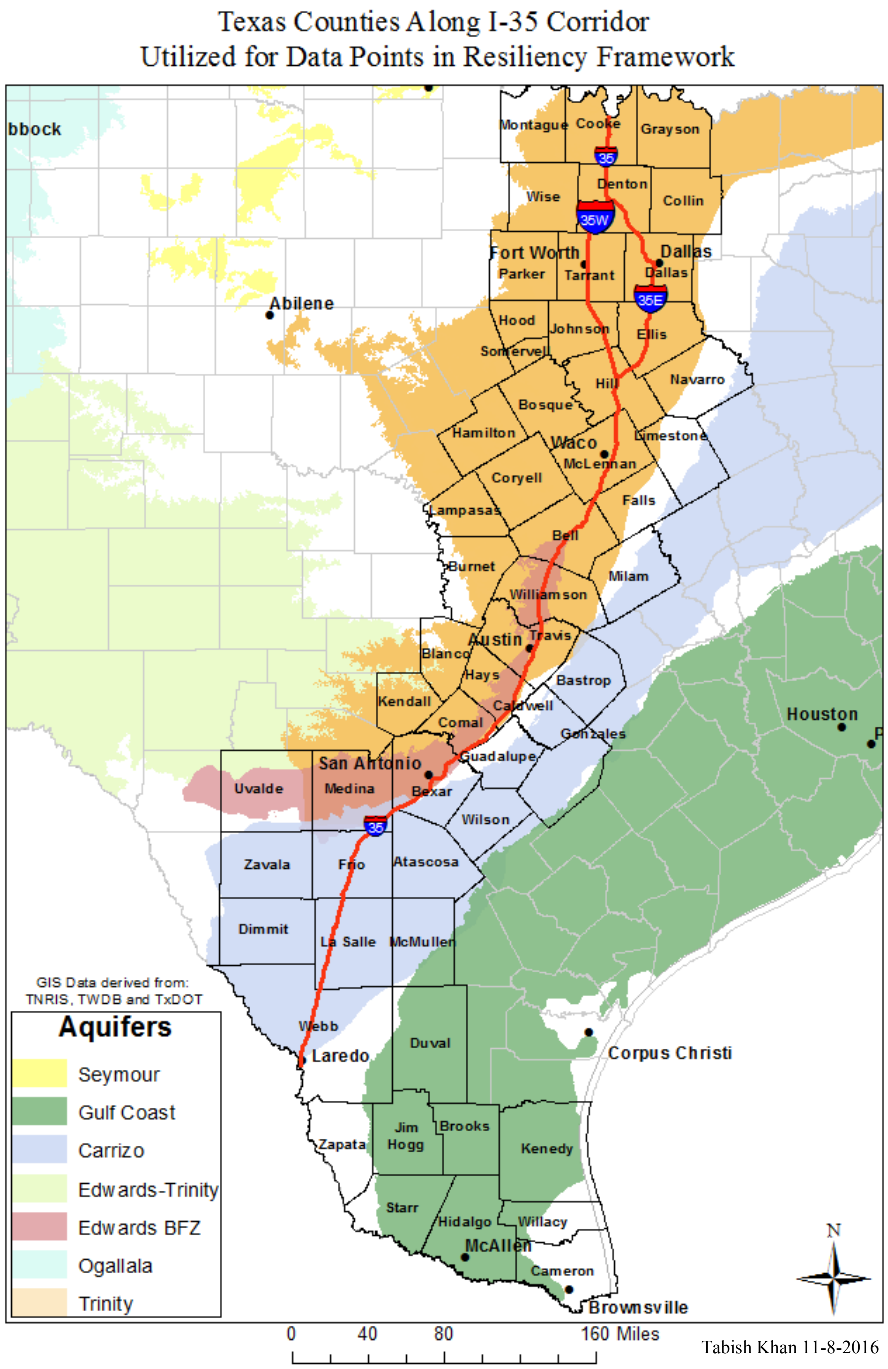
Design of RRF Graphic

The graphic design and layout were inspired by the Household Vulnerability Diagram by Richmond, et al., (2015). This diagram allowed the simultaneous display and comparative analysis of multiple variables and cases at once. There are many other categories, sub-variables, and spatial variables which can be integrated and analyzed in this framework, however, time constraints and data availability have limited this case study. Once data for each variable is compiled and processed into the "1-10" scaled values. It can then be plotted on the RRF diagram. Connecting the plotted points between neighboring variables yields a polygon which depicts a general view of the relative resilience of the county being measured with all other counties in the dataset.

Proof-of-Concept

The study area to which the framework was applied is what has been called the "I-35 corridor" (Fig. 3.6). This is not a well-defined list of counties but rather an ambiguous mass of counties which are located along or near the path of Interstate-35 as it runs from North to South Texas. Cities along the I-35 corridor are some of the most populous in Texas (Table 1-1) and include major population centers such as Dallas, Fort Worth, Waco, Austin, San Antonio, San Marcos, Brownsville, and McAllen. Brownsville and McAllen are not along the route of I-35, however, they are relatively near the study area and statistically significant when discussing water shortages in Texas.

Figure 3.6: Study Area



GIS layers derived from the Texas Natural Resources Information System, the Texas Water Development Board, and the Texas Department of Transportation.

Chapter 4: Results

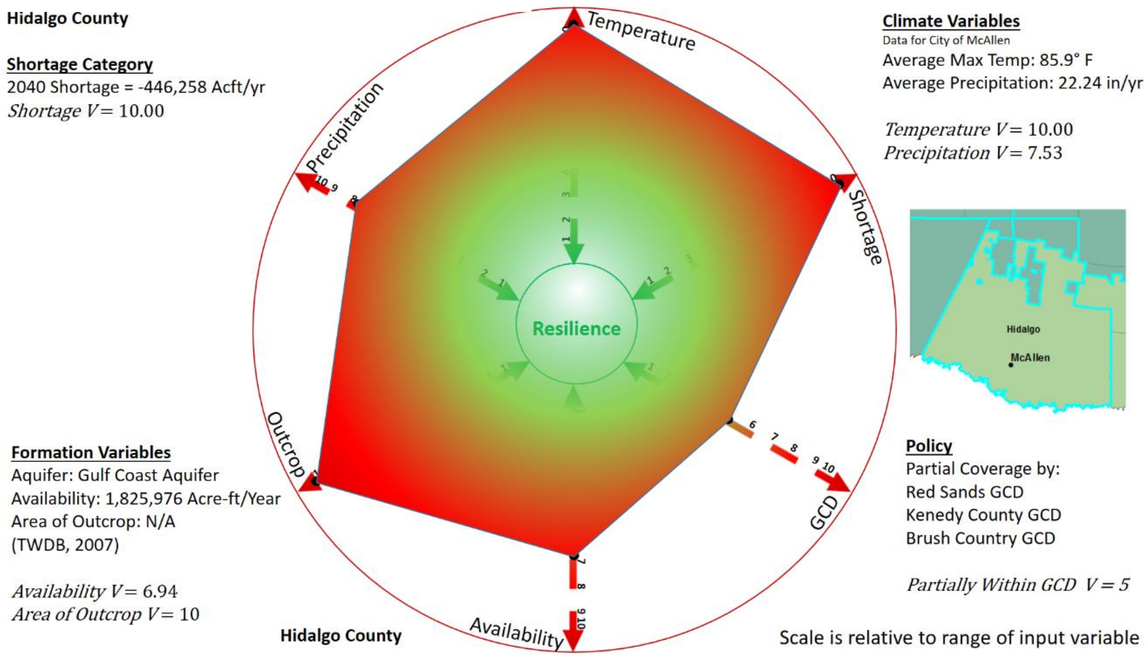
Discussion

The lowest availability value in this dataset is 200 acre-ft/yr from the Marathon Aquifer. The highest availability in the dataset is 5,968,260 acre-ft from the Ogallala Aquifer. The lowest outcrop area in the dataset is 0 $miles^2$ since multiple aquifers have no reported outcrop. The highest outcrop area is 32,294 $miles^2$ over the Edwards-Trinity Plateau Aquifer (TWDB, 2007).

The lowest precipitation value in the dataset is 9.69 inches/year in El Paso (Table 3.2) (USCD, 2016). The highest total annual precipitation dataset is 60.55 inches/year in Port Arthur (USCD, 2016). The lowest value in the dataset is 70.9 degrees Fahrenheit in Amarillo (USCD, 2016). The highest average maximum temperature in the dataset which is 85.9 degrees Fahrenheit in McAllen (USCD, 2016).

Figures 4.1 and 4.2 depict the RRF results for Hidalgo and Dallas County along with the values on which those results were based.

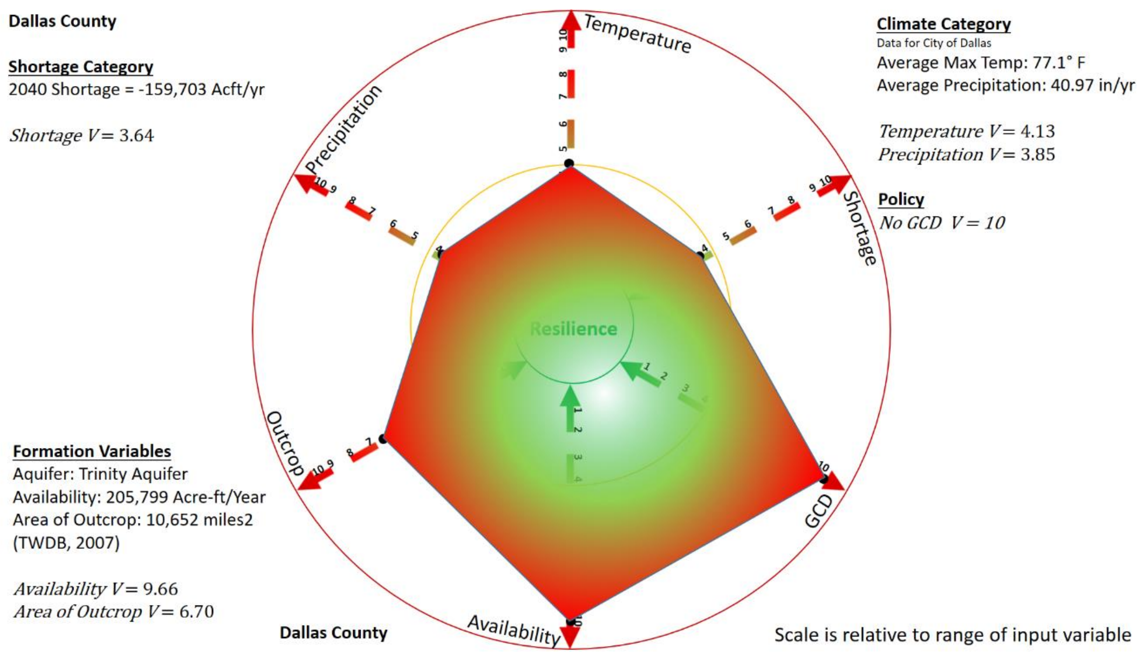
Figure 4.1: RRF Results for Hidalgo County



Initial analysis of this result indicates Hidalgo County is expecting extreme shortages relative to other counties in the dataset. The dataset for this variable only included counties along the I-35 corridor study area, so these results are spatially limited. Most variables for Hidalgo County indicate high vulnerability and the only apparent resilience factor appears to be partial coverage by a GCD. Most of Hidalgo County is not located within a GCD, however a small portion is within the jurisdiction of the Red Sands GCD, Kenedy GCD, and Brush Country GCD. This may be due to Hidalgo County's reliance on surface water since it and the rest of Region M obtain the majority of their water from the Rio Grande (RGRWPG, 2015). The majority of the Gulf Coast Aquifer underlying this area is actually brackish (RGRWPG, 2015). In addition, the median income of

Hidalgo County is $33,218, with 35% of the population living below the poverty line (RGRWPG, 2015). Water management strategies for this area are focused on conservation, especially in the irrigation sector which is expecting a decrease in demand due to urbanization (RGRWPG, 2015). However, the combination of vulnerability factors combined with the potential for drought are indicative of difficulties in the future if conservation goals are not met.

Figure 4.2: RRF Results for Dallas County



Dallas County also scores high vulnerability rates, when viewed from a groundwater perspective. This is due to its high dependence on surface water resources (RCWPG, 2015). Dallas County is facing significant shortages as well, however, the relativity feature of the RRF skews this metric due to the immense shortages of other counties evaluated in the case study. Management strategies for Region C, within which Dallas County is located, include new surface water projects (RCWPG, 2015). This will increase the resilience factor of this region if more extreme but less frequent precipitation is to be expected. Longer and more frequent droughts, however, strain surface water resources and can be detrimental unless a diverse water portfolio is utilized.

Figures 4.3 - 4.8 depict the RRF results of I-35 corridor counties in North Texas, North Central Texas, the Lower Colorado, South Central Texas, the Rio Grande Region, as well as several counties in the Coastal Bend.

Figure 4.3: RRF Results for North Texas

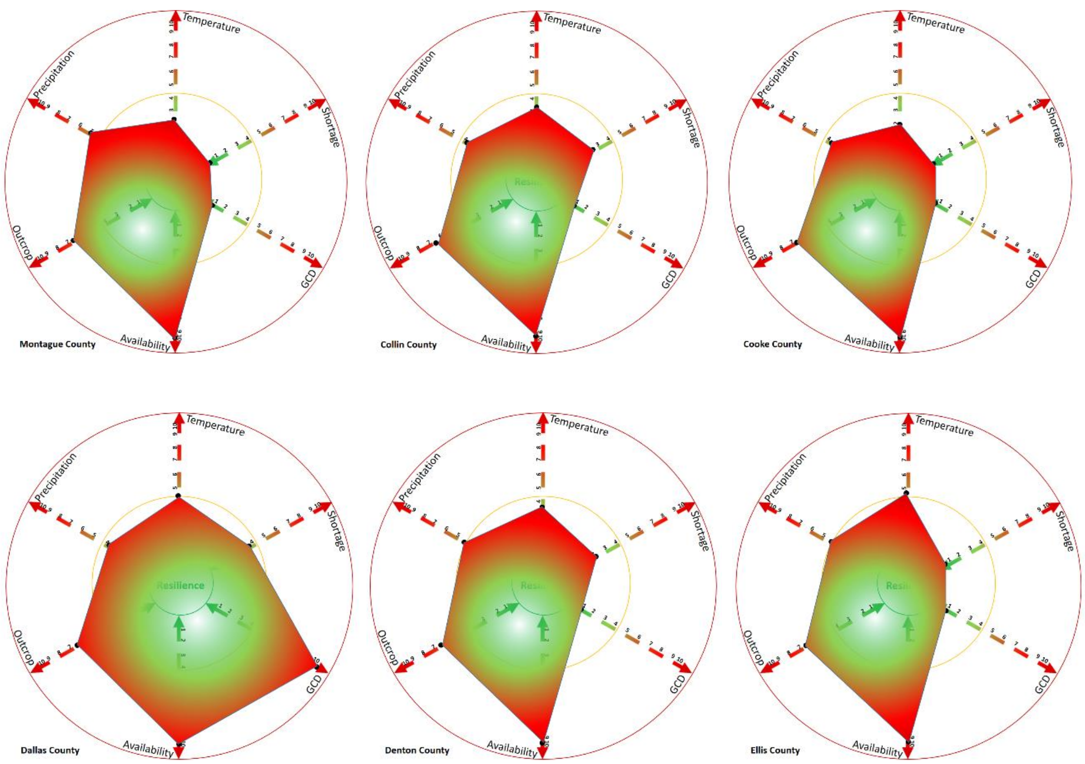
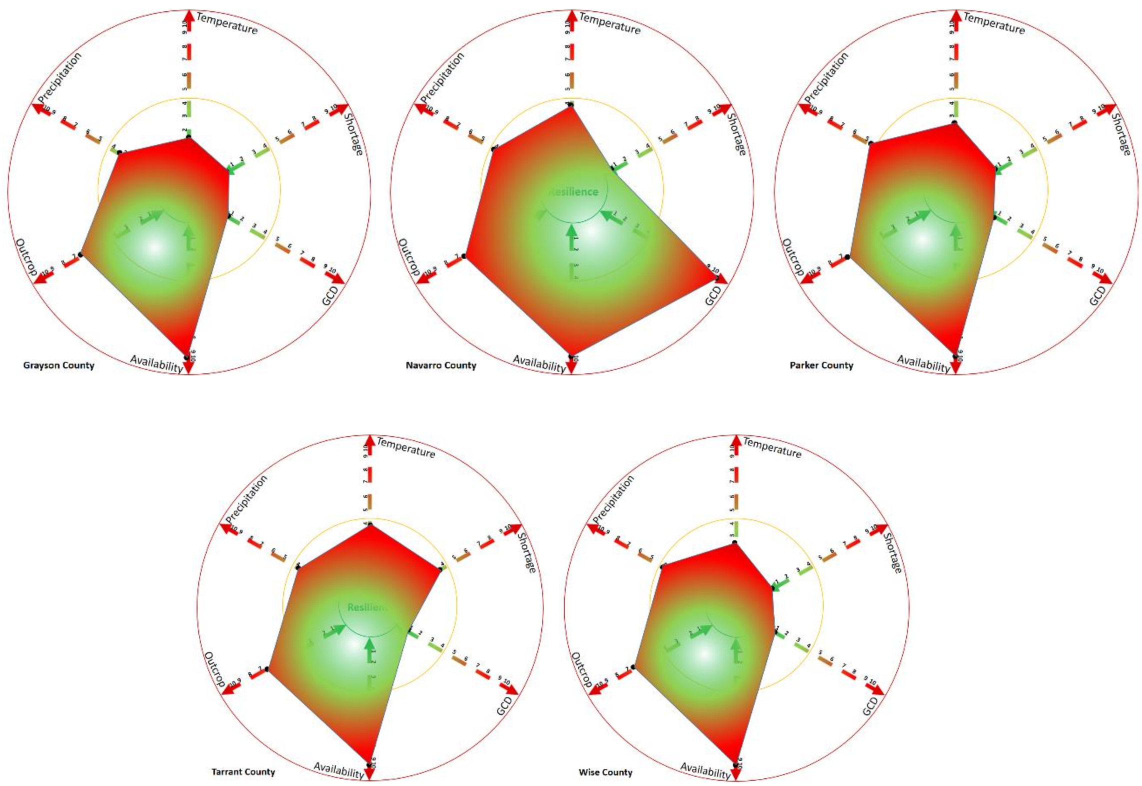


Figure 4.3 Continued: RRF Results for North Texas



Counties in North Texas are mostly dependent upon surface water resources (RCWPG, 2015). These counties overlie the Trinity Aquifer which scored low on the resiliency scale in relation to the Edwards-Trinity Plateau with its relatively large outcrop and the Ogallala which is estimated to have the highest availability in this dataset (Table 3-3). These counties do not appear to be expecting shortages in the near future, however, this situation could change with the variability of climate. Currently, precipitation and temperature averages appear to be relatively moderate. Most counties also appear to reside within GCDs except Dallas and Navarro. Counties in and around the DFW Metroplex are expecting the largest municipal growth in the region and could benefit from diversification of their water supply.

Figure 4.4: RRF Results for North Central Texas

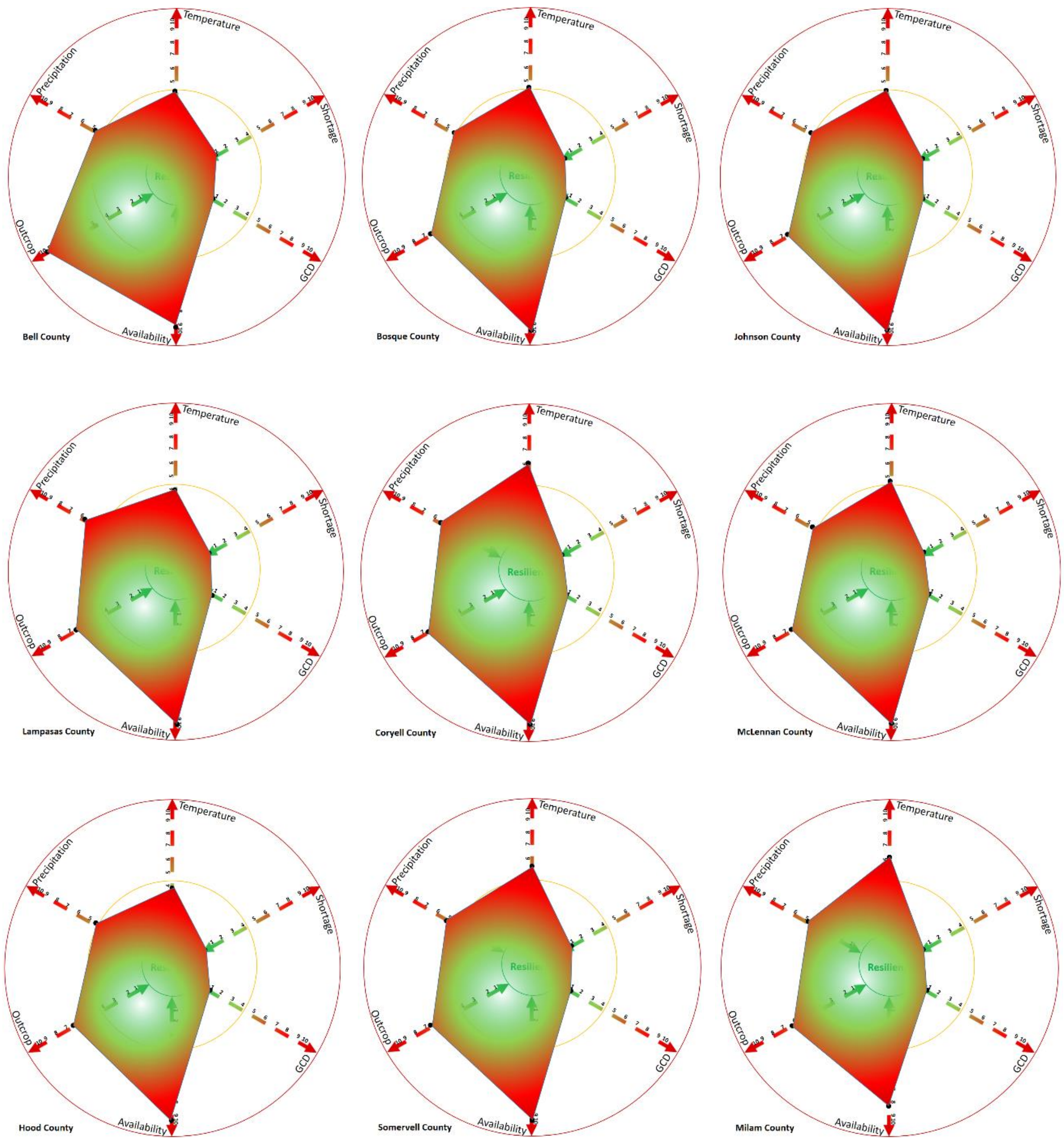
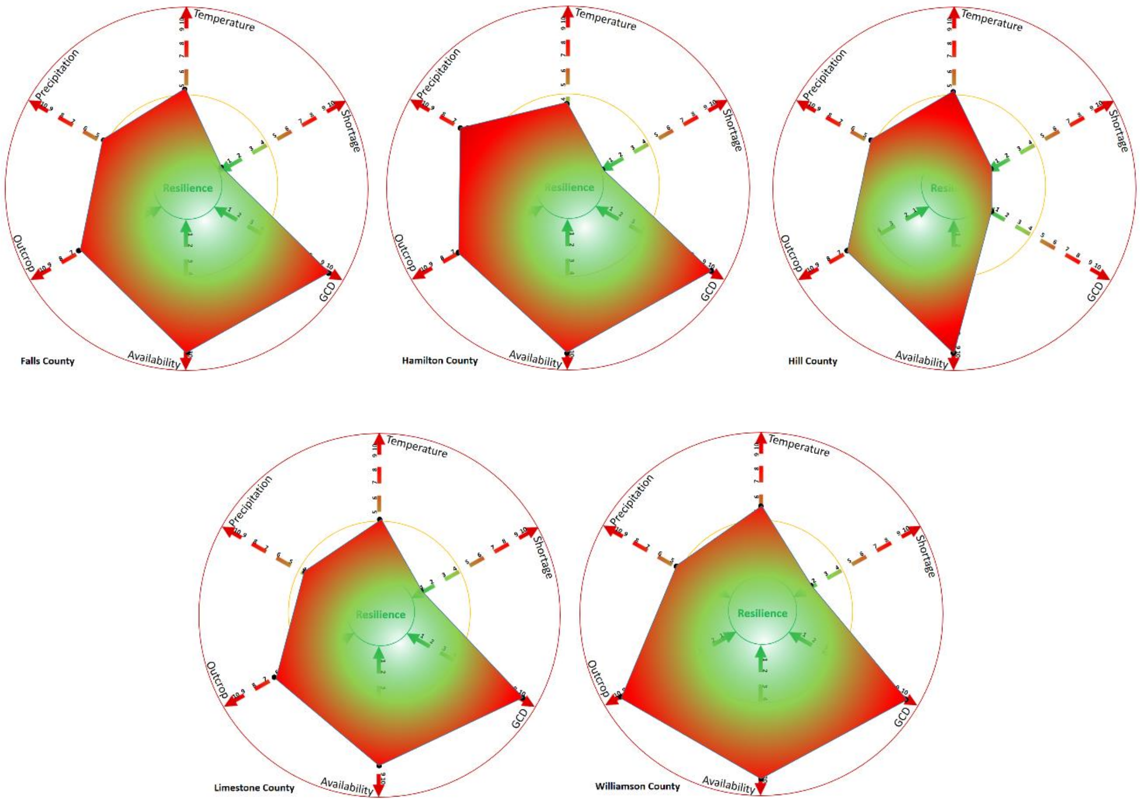
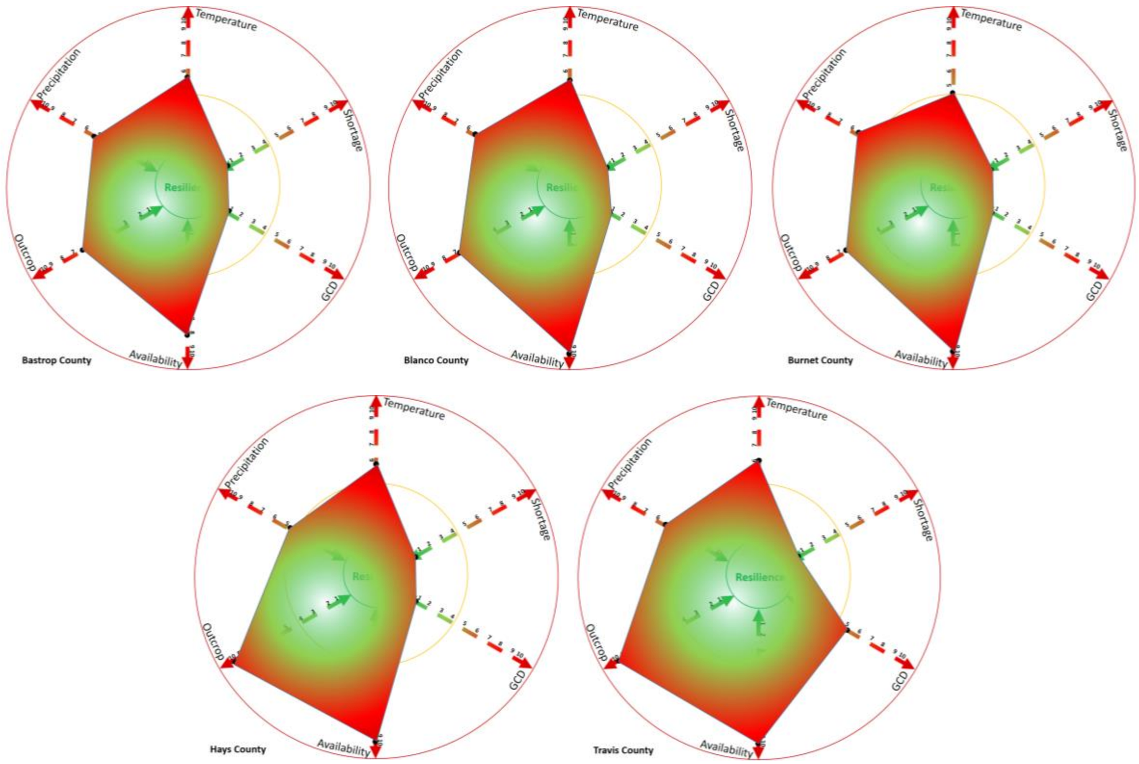


Figure 4.4 Continued: RRF Results for North Central Texas



North Central Texas counties are in many ways similar to North Texas counties. They also overly the Trinity Aquifer are not expecting significant shortages, and are dependent on surface water (BGRWPG, 2015). The same threats of prolonged drought and variability in precipitation apply to these counties as well. Currently, relative temperatures and precipitation rates are moderate in this region.

Figure 4.5: RRF Results for Lower Colorado Counties



The counties of the Lower Colorado Region have a wider variety of water sources. These sources include the Lower Colorado River basin, the Edwards Aquifer, and the Trinity Aquifer (LCRWPG, 2015). These counties are not expecting shortages in the coming decades, are mostly covered by GCDs, and have relatively moderate temperatures and precipitation. In addition, the sensitive Edwards Aquifer which underlies this area is monitored and managed by the Edwards Aquifer Authority.

Figure 4.6: RRF Results for South Central Texas

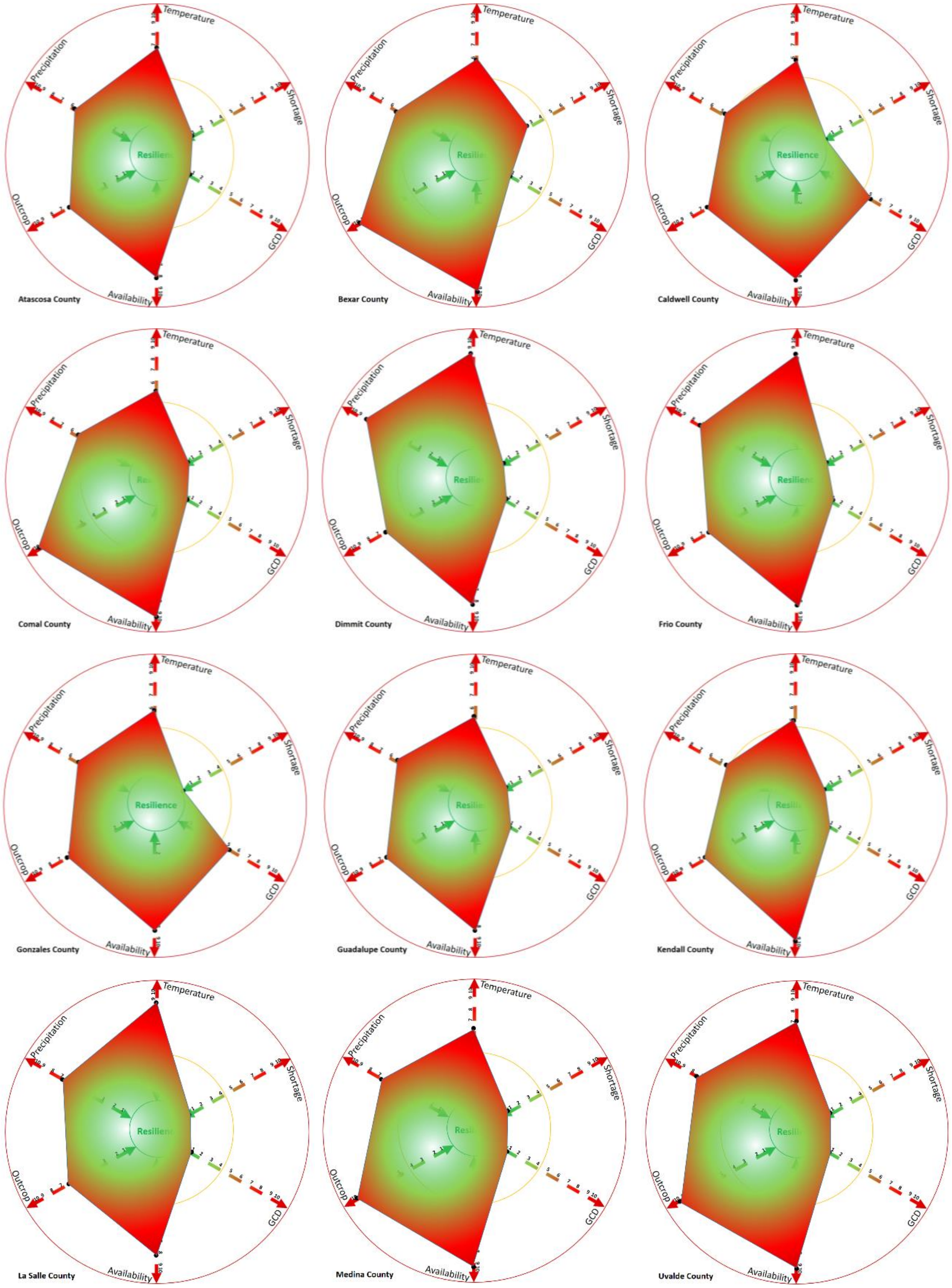
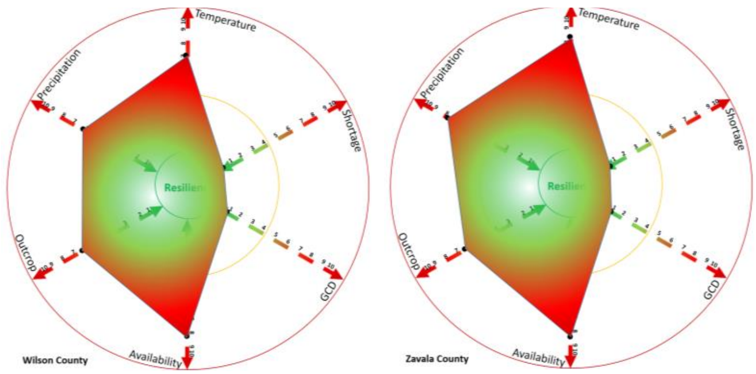
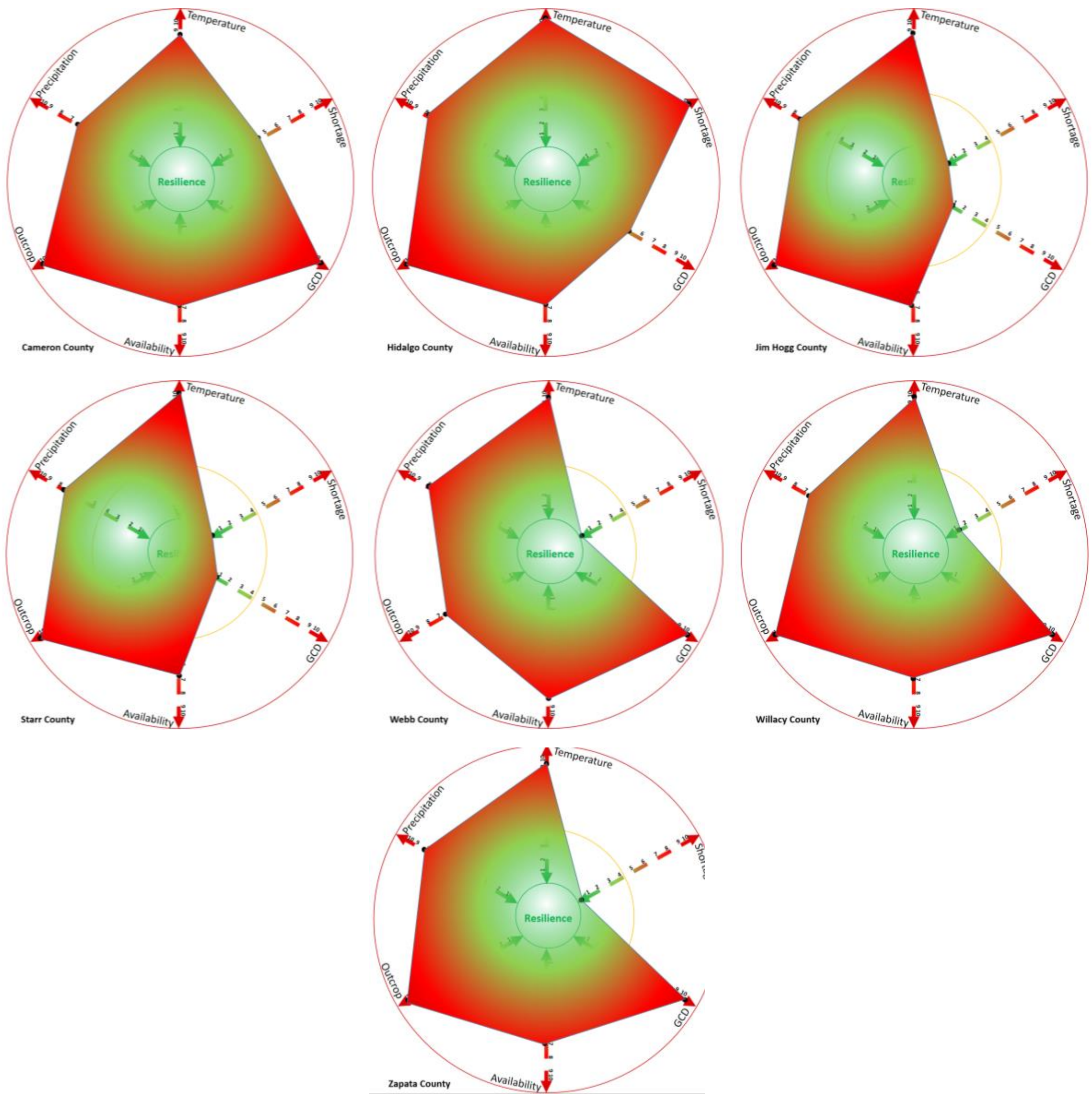


Figure 4.6 (Continued): RRF Results for South Central Texas



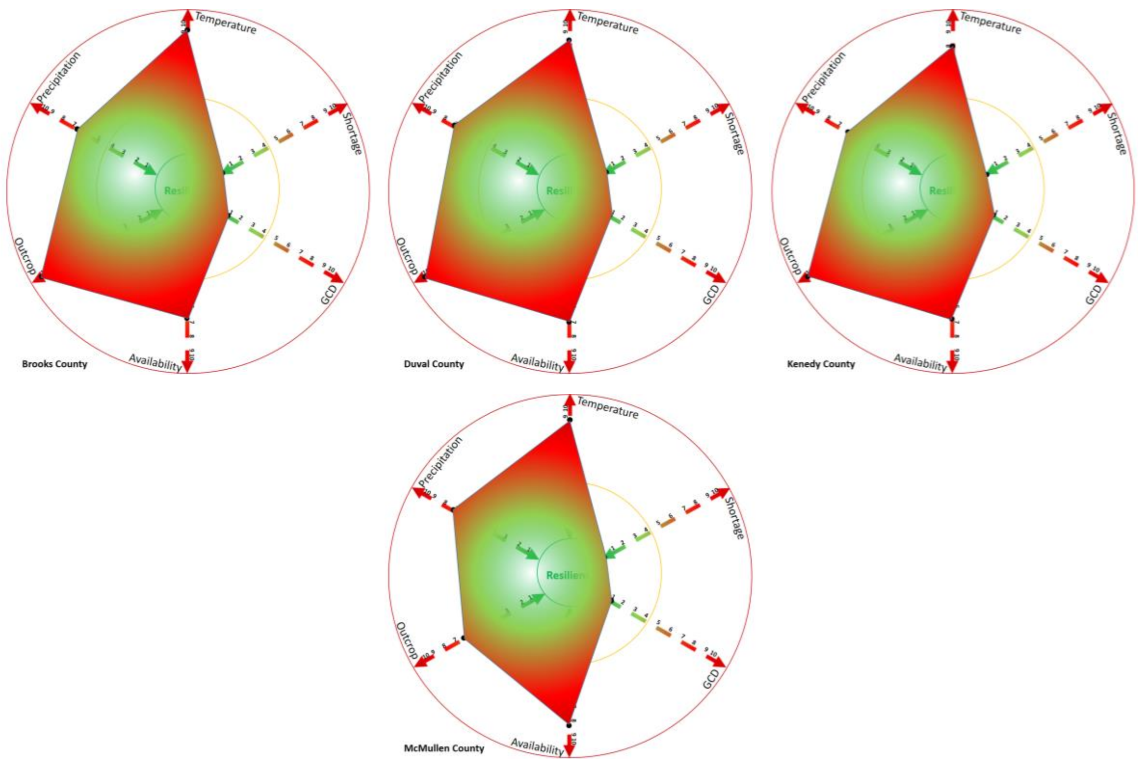
South Central Texas Counties include the San Antonio area as well as the Winter Garden Region. These counties depend on multiple aquifers and place a heavy municipal and agricultural demand on those formations (SCTRWPG, 2015). San Antonio's municipal supply is principally extracted from the Edwards Aquifer and the limitations of this supply has caused San Antonio to ambitiously engage in conservation. In addition, San Antonio is pursuing alternative water management strategies including aquifer storage and recovery as well as brackish desalination. The Winter Garden agricultural region is heavily dependent on the Carrizo-Wilcox Aquifer for year-round irrigation, however, demand expectations for this region are shifting from agriculture to municipal in the long term. Temperatures for this region are generally higher than areas further north and several counties also see less average precipitation. Most of this region is under the jurisdiction of GCDs. Given the municipal growth as well as the limited supply from Edwards Aquifer, development of alternative supplies is ongoing to fulfill future demands.

Figure 4.7: RRF Results for Rio Grande Counties



The counties of the Rio Grande River Basin are heavily dependent on it for their water supply (RGRWPG, 2015). The Gulf Coast Aquifer in this region is brackish and would require costly desalination to be suitable for municipal or agricultural use (RGRWPG, 2015). The socioeconomic conditions of this region are poor. Therefore costly water management strategies could place vulnerable user groups at risk (RGRWPG, 2015). The current water management strategies for this region are heavily dependent on conservation and the expectation that irrigation demand will shift to municipal demand (RGRWPG, 2015). Unfortunately, like North Texas, high dependence on surface water and the potential for droughts make this a vulnerable region. On average, this region has the highest temperatures as well as poor precipitation levels (Table 3-2). This region is also anticipating some of the highest shortages in the State.

Figure 4.8: RRF Results for Coastal Bend Counties



The counties of the Coastal Bend region are relatively similar and have a water portfolio mostly dependent on surface water supplies. While there is groundwater use in this region, it is limited because sources from the Carrizo-Wilcox and Gulf Coast Aquifers can be saline (CBRWPG, 2015). This region has relatively high temperatures and moderate precipitation (Table 3-2). All four of the counties evaluated in this study are covered by GCDs and do not anticipate shortages in the coming years.

Chapter 5: Conclusions, Discussion, and Suggestions for Future Research

The diverse geographic conditions across Texas result in a variety of climate conditions, resource availability, demand types, and population concentrations. This set of variables requires prioritization when setting policy and complicates blanket approaches that affect the entire State and its different user groups. North, Central, and South Texas regions are all facing immense growth in their urban population centers. It has so far been ethically acceptable if not economically harmful to deny agricultural users water in times of shortages, however, municipal demands must be met and to withhold water from those users would be a public policy and resource management failure. Water policy in Texas is fractured and in many ways could benefit from a more centralized planning perspective. The typical planning cycle of a GCD does involve a joint planning process with their respective GMAs, however, this process seems excessively complex. A more efficient method could involve an entity which has the authority and capacity to manage an aquifer as a whole and not by county. Since GMAs already have boundaries more aligned with their respective aquifers, it would make sense to elevate permitting and management functions to the GMA level. The heavy dependence on surface water without significant alternatives appears to be the most significant weakness in the management strategies of several regions. Diversification and conservation will most likely aid the mitigation of challenges brought on by population growth, drought, and climate change.

Several factors can be further broken down and researched to develop this framework. An assessment of the factors which contribute to effective groundwater management and not just the existence of GCDs would contribute to the framework. In addition, socioeconomic variables need to be considered in order to add reinforcement to an area's vulnerability in the case that alternative water management strategies are needed. Refined equations could compensate for the skewing of proportional values when analyzing availability and shortages. The immense disparity within the ranges resulted in the minimization of significant variables which fell out of scope. A surface water dependence variable would have readily placed into perspective the balance of sources which each county depended on and would reduce explanatory measures needed to convey information from the diagram. In conclusion, there are many challenges ahead for Texas water planners but frameworks and indicators can help bridge science and policy by making data more accessible.

Assumptions and Limitations

Assumptions in this framework include the drought of record of the 1950's as a minimum benchmark for some of the data that is utilized in the framework.

Limitations of the framework include the lack of water quality indicators. Additionally, the framework would be more accurate and meaningful if the following factors were added:

- Additional recharge variables to form a more accurate evaluation of recharge potential.
- Dependence of an area on surface water resources would allow for mitigation of variables which otherwise indicate strong groundwater vulnerability. This factor would also indicate general vulnerability to drought and climate change.
- Additional data points. Due to the scale's relative nature, as more data is entered, more accuracy is achieved. However, the datasets must be limited to any level of political boundaries to maintain relevance to public policy. In addition, the larger the boundaries of the area being measured, the more data points will be needed to achieve higher resolution.

Additionally, this framework and the resulting data interpretations are limited by the scope of the entered data. Therefore, the more data that is utilized, the higher the resolution and relative indication of resilience. Due to the fragmented nature of water planning this case study is also based on fragmented data which reduces the accuracy of relative values. Variables which are chosen to represent resilience and the depth of the data representing those variables are also a potential weakness on the application side of the RRF. Lastly, while the effects of climate change and droughts could be mitigated for by prioritizing regional water management strategies, the exact threat levels to discrete areas of Texas are still unknown.

Appendix 1: Previous Research and Related Frameworks

Community Resilience Frameworks

The ARCAB framework analyzes the effects of climate change on the resilience and vulnerability of communities (ARCAB, 2012). ARCAB cites poverty as a critical contributor to vulnerability since the poor are less likely to have the resources necessary to cope with the predicted effects of climate change thereby reducing their adaptive capacity (ARCAB, 2012). For a community, individual, household, economy, or any organization, high adaptive capacity improves resilience against climate change (ARCAB, 2012). Multiple organizations have adopted the concept of adaptive capacity with indicators such as poverty levels, food security, and water security (ARCAB, 2012) (DFID, 2014).

The DFID methodology recommends that resilience indicators:

> *Seek to capture changes in people's behavior or circumstances that will make them better able to anticipate, avoid, plan for, cope with, recover from, and adapt to the shocks and stresses that they are likely to face in the foreseeable future - (DFID, 2014).*

The focus of the DFID method is on the adaptive capacity of communities to increase resilience by reducing dependence. When applied to water management, this would imply conservation strategies such as drought resistance crops or the use of micro-irrigation (DFID, 2014).

The Household Vulnerability Framework by Richmond et al., (2015) includes human vulnerability from socioeconomic and environmental stress, which can be amplified by increasing populations (Richmond et al., 2015). The Household Vulnerability Framework also states the lack of appropriate resolution for individual groups when evaluating data on regional scales (Richmond et al., 2015). Within a region, various groups of individuals can be affected differently (Richmond et al., 2015). So even if an area has sufficient water supply from proposed water management strategies it may not have high resilience. Consideration should be given to how accessible is a water supply to different user groups and socioeconomic levels. As the price of water increases, the poor will be at a disadvantage, thereby reducing their resilience. The Household Vulnerability scale also organizes indicators of vulnerability into “baskets” - an approach similar to that used by Busby et al., (2012) (Richmond et al., 2015). The Household Vulnerability indicators were normalized within each basket between zero and one, with zero representing the poorest condition for a household and one being optimal (Richmond et al., 2015). Richmond et al., (2015) cited fieldwork, literature reviews, direct observations, and expert opinions as the basis on which weights were given to each basket to determine vulnerability scores. After normalization, a basket score was calculated by taking the average score for all of the variables within the basket (Richmond et al., 2015). The basket score was multiplied by the basket weighting metric to derive a final vulnerability score out of 100 (Richmond et al., 2015).

Groundwater Frameworks

There are also frameworks which focus solely on water issues such as a framework developed by the Environment Protection Agency (EPA) known as the DRASTIC method. The DRASTIC method contains parameters such as depth to groundwater, net recharge, aquifer media, soil media, general topography, impact of the vadose zone, and the hydraulic conductivity of the aquifer (Bataineh et al., nd). By these measures, the DRASTIC approach is highly focused on water quality issues (Bataineh et al., nd). The DPSIR framework, developed by the European Environment Agency (EEA) for its analysis of water-related issues, analyzes the factors which contribute to water supply and quality as well as demand and user metrics (Kristensen, 2004). Like the DRASTIC method, DPSIR is an acronym for the categories of variables being measured. "D" represents the driving forces; "P" represents pressures on the environment; "S" represents the consequent state for the environment; "I" represents impacts on the environment; and "R" represents the responses to these effects by humans (Fig. 2.1) (Kristensen, 2004). The DPSIR framework offers indicators and a process to evaluate water resilience, however, it does not appear to offer a measurement system to quantify these variables.

Groundwater Resilience Frameworks and Research

The study of groundwater resilience can help to identify the circumstances which cause high vulnerability (Stigter et al., 2011). Hashimoto et al., (1982) measured groundwater performance through resilience, vulnerability, and reliability. Reliability conveyed the frequency or probability that a system maintained a satisfactory state (Hashimoto et al., 1982). Peters et al., (2004), employed Hashimoto's performance indicators to assess groundwater performance during drought and made calculations from precipitation, evapotranspiration, recharge, and discharge variables. Ritchey et al., (2015) added groundwater storage as a factor of groundwater resilience. Groundwater's ability to provide resilience to a community is based on its typically larger storage capacity and higher residence times than those of typical inland surface water sources (Anderies et al., 2006) (Hugman et al., 2012) (Katic and Grafton, 2011) (Lapworth et al., 2012) (MacDonald et al., 2011) (Shah, 2009) (Sharma and Sharma, 2006) (Taylor et al., 2013). Despite the many frameworks and analysis tools available, a method to analyze and visually present multi-criteria resilience indicators for assessment on a relative basis was not found.

Appendix 2: Tables

Table 1-1							
Data derived from 2017 Texas State Water Plan	Projected Population Growth in Texas by Regional Planning Areas						
Region	**2020**	**2030**	**2040**	**2050**	**2060**	**2070**	**% Growth**
A	419,000	461,000	504,000	547,000	592,000	639,000	53
B	206,000	214,000	219,000	223,000	226,000	229,000	11
C	7,504,000	8,649,000	9,909,000	11,260,000	12,742,000	14,348,000	91
D	831,000	908,000	989,000	1,089,000	1,212,000	1,370,000	65
E	954,000	1,086,000	1,208,000	1,329,000	1,444,000	1,551,000	63
F	701,000	767,000	825,000	885,000	944,000	1,003,000	43
G	2,371,000	2,721,000	3,097,000	3,495,000	3,918,000	4,351,000	84
H	7,325,000	8,208,000	9,025,000	9,868,000	10,766,000	11,743,000	60
I	1,152,000	1,234,000	1,310,000	1,389,000	1,470,000	1,554,000	35
J	141,000	154,000	163,000	171,000	178,000	185,000	31
K	1,737,000	2,065,000	2,382,000	2,658,000	2,928,000	3,243,000	87
L	3,001,000	3,477,000	3,920,000	4,336,000	4,770,000	5,192,000	73
M	1,961,000	2,379,000	2,795,000	3,212,000	3,626,000	4,029,000	105
N	615,000	662,000	693,000	715,000	731,000	745,000	21
O	540,000	594,000	646,000	698,000	751,000	802,000	4
P	50,000	52,000	53,000	54,000	55,000	56,000	12
Texas	29,508,000	33,631,000	37,738,000	41,929,000	46,353,000	51,040,000	73

Table 2-1

Table derived from (Hugman et al., 2012)	Overview of Scenarios and Optimized Sustainable Yield					
Scenario	**Distribution of R**	**Distribution of A**	**Storage coefficient**	**Location of PS wells**	**Sustainable yield** % of MAR	hm^3
1Aia	Distributed	Seasonal	Optimized	Concentrated	73%	75.9
2Aia	Concentrated	Seasonal	Optimized	Concentrated	70%	72.8
1Aib	Distributed	Seasonal	Optimized	Distributed	—	—
2Aib	Concentrated	Seasonal	Optimized	Distributed	—	—
1Aiia	Distributed	Seasonal	Reduced 2x	Concentrated	70%	72.8
2Aiia	Concentrated	Seasonal	Reduced 2x	Concentrated	67%	69.7
1Aiiia	Distributed	Seasonal	Reduced 5x	Concentrated	40%	41.6
2Aiiia	Concentrated	Seasonal	Reduced 5x	Concentrated	35%	36.4
1Bia	Distributed	Constant	Optimized	Concentrated	79%	82.4
2Bia	Concentrated	Constant	Optimized	Concentrated	76%	79
1Bib	Distributed	Constant	Optimized	Distributed	79%	82.4
2Bib	Concentrated	Constant	Optimized	Distributed	74%	77

A = public supply withdrawal
MAR = mean annual recharge
PS = public supply
R = Recharge

Table 2-2		
List derived from (Schipper et al., 2015)	**A Sampling of Existing Resilience Frameworks**	
Organization	**Framework Title**	**Source**
Rockefeller Foundation	Asian Cities Climate Change Resilience	(Tyler et al., 2014)
Global Change System for Analysis, Research, and Training	Assessments of Impacts and Adaptations of Climate Change Sustainable Livelihood Approach	(Elasha et al., 2005)
Sea Change	Action Research for Community Based Adaptation	(ARCAB, 2012)
Rockefeller Foundation	ARUP's City Resilience Framework	(ARUP, 2014)
UK Department for International Development	Resilience and Adaptation to Climate Extremes and Disasters Framework	(DFID, 2014)
United Nations Development Programme	Community-Based Resilience Analysis Framework	(UNDP, 2013)
Food and Agricultural Organization and World Food Program	Principles of Resilience Measurement for Food Insecurity	(Barret and Constas, 2013)
United Nations University - Institute for Environment and Human Security	Capital-Based Approach to Community Disaster Resilience	(Mayunga, 2007)
Feinstein International Center	Livelihood and Resilience Framework	(Vaitla, 2012)
International Institute for Sustainable Development	Climate Resilience and Food Security	(IISD, 2013)
UN Food and Agriculture Organization's	Self-evaluation and Holistic Assessment of Climate Resilience of Farmers and Pastoralists Framework	(Choptiany et al, 2015)
International Institute for Environment and Development	Tracking Adaptation and Monitoring Development	(Brooks et al., 2013)
Non-Government Organization	Characteristics of a Disaster Resilient Community	(Twigg, 2009)
United Nations International Strategy for Disaster Risk Reduction	Disaster Resilience Scorecard for Cities	(UNISDR, 2014)
United States Agency for International Development	Measurement for Community Resilience	(USAID, 2013)
United States Agency for International Development	Coastal Resilience (Indian Ocean Tsunami Warning System Program)	(USAID, 2007)

Table 3-1

Data derived from 2016 Regional Water Plans B, C, G, K, L, M, and N	S = Shortage (Acre-Ft/Year) Scale Value (V) = $10(S_{MAX}-S)/(S_{MAX}-S_{MIN})$											
	2020		2030		2040		2050		2060		2070	
County	Shortage	V	Shortage	V	Shortage	V	Shortage	V	Shortage	V	Shortage	V
Atascosa	-171	0.11	-257	0.11	-333	0.10	-409	0.10	-484	0.10	-579	0.09
Bastrop	-4,184	0.20	-11,327	0.35	-15,883	0.45	-22,596	0.59	-32,730	0.80	-47,187	1.02
Bell	No data	No data	No data	No data	-16,675	0.47	No data	No data	No data	No data	-42,904	0.93
Bexar	-61,851	1.52	-88,049	2.08	-112,441	2.59	-141,763	3.21	-172,269	3.84	-202,304	4.11
Blanco	-48	0.11	-105	0.10	-138	0.10	-179	0.10	-209	0.09	-230	0.08
Bosque	No data	No data	No data	No data	-6,955	0.25	No data	No data	No data	No data	-14,002	0.36
Brooks	1,647	0.07	1,498	0.07	1,357	0.07	1,189	0.07	1,022	0.06	848	0.06
Burnet	-1,258	0.14	-2,401	0.15	-4,718	0.20	-6,850	0.24	-8,769	0.28	-10,457	0.28
Caldwell	-188	0.11	-685	0.11	-1,326	0.12	-2,134	0.14	-3,024	0.15	-3,907	0.15
Cameron	-206,026	4.83	-193,330	4.46	-187,351	4.25	-183,864	4.14	-182,476	4.07	-198,668	4.04
Collin	-18,865	0.54	-65,722	1.58	-105,470	2.44	-145,168	3.29	-177,270	3.95	-207,655	4.22
Comal	-5,153	0.23	-7,942	0.28	-14,360	0.41	-20,778	0.55	-27,492	0.69	-34,079	0.76
Cooke	-849	0.13	-288	0.11	-300	0.10	-461	0.10	-1,058	0.11	-5,017	0.18
Coryell	No data	No data	No data	No data	-1,577	0.13	No data	No data	No data	No data	-5,234	0.18
Dallas	-42,674	1.08	-101,656	2.39	-159,703	3.64	-206,626	4.64	-248,412	5.50	-280,615	5.67
Denton	-12,241	0.39	-47,075	1.16	-86,617	2.02	-128,970	2.93	-174,830	3.90	-216,283	4.39
Dimmit	-8,790	0.31	-8,991	0.30	-8,203	0.28	-6,594	0.24	-4,013	0.17	-3,169	0.14
Duval	4,679	0.00	4,413	0.00	4,292	0.00	4,163	0.00	4,002	0.00	3,824	0.00
Ellis	-1,611	0.14	-5,680	0.23	-14,495	0.42	-24,579	0.63	-43,984	1.05	-73,554	1.54
Falls	No data	No data	No data	No data	-425	0.10	No data	No data	No data	No data	-511	0.09
Frio	0	0.11	0	0.10	0	0.10	0	0.09	0	0.09	-19	0.08
Gonzales	0	0.11	0	0.10	0	0.10	-249	0.10	-92	0.09	-373	0.08
Grayson	-86	0.11	-8,106	0.28	-10,067	0.32	-13,483	0.39	-21,829	0.56	-36,244	0.80
Guadalupe	-1,499	0.14	-4,244	0.20	-7,272	0.26	-11,864	0.35	-16,895	0.46	-21,910	0.51
Hamilton	No data	No data	No data	No data	-175	0.10	No data	No data	No data	No data	-17	0.08
Hays	-531	0.12	-2,396	0.15	-6,345	0.24	-11,412	0.34	-16,970	0.46	-23,294	0.54
Hidalgo	-431,898	10.00	-439,406	10.00	-446,258	10.00	-450,263	10.00	-454,524	10.00	-497,403	10.00
Hill	No data	No data	No data	No data	-32	0.10	No data	No data	No data	No data	-69	0.08
Hood	No data	No data	No data	No data	599	0.08	No data	No data	No data	No data	-827	0.09
Jim Hogg	-239	0.11	-237	0.10	-244	0.10	-295	0.10	-368	0.10	-404	0.08
Johnson	No data	No data	No data	No data	-6,383	0.24	No data	No data	No data	No data	-16,549	0.41
Kendall	0	0.11	0	0.10	0	0.10	-650	0.11	-1,639	0.12	-2,613	0.13
Kenedy	61	0.11	44	0.10	43	0.09	42	0.09	41	0.09	41	0.08
La Salle	-4,110	0.20	-4,315	0.20	-3,979	0.18	-2,746	0.15	-851	0.11	-147	0.08
Lampasas	No data	No data	No data	No data	-2,012	0.14	No data	No data	No data	No data	-2,707	0.13
Limestone	No data	No data	No data	No data	-18,801	0.51	No data	No data	No data	No data	-42,346	0.92
McLennan	No data	No data	No data	No data	-1,404	0.13	No data	No data	No data	No data	-13,812	0.35
McMullen	449	0.10	452	0.09	455	0.09	456	0.08	456	0.08	456	0.07
Medina	-32,415	0.85	-30,285	0.78	-28,211	0.72	-26,225	0.67	-24,344	0.62	-22,738	0.53
Milam	No data	No data	No data	No data	-76	0.10	No data	No data	No data	No data	-6,757	0.21
Montague	-1,315	0.14	-250	0.11	-281	0.10	0	0.09	0	0.09	0	0.08
Navarro	-8,000	0.29	-17,038	0.48	-17,838	0.49	-19,144	0.51	-21,055	0.55	-23,704	0.55
Parker	-3,349	0.18	-6,752	0.25	-11,025	0.34	-18,031	0.49	-32,667	0.80	-51,749	1.11
Somervell	No data	No data	No data	No data	-35,915	0.89	No data	No data	No data	No data	-35,864	0.79
Starr	-7,992	0.29	-6,579	0.25	-5,199	0.21	-6,176	0.23	-7,140	0.24	-8,127	0.24
Tarrant	-24,130	0.66	-82,442	1.96	-151,925	3.47	-207,390	4.66	-257,690	5.71	-305,928	6.18
Travis	-3,199	0.18	-19,203	0.53	-27,658	0.71	-41,766	1.01	-85,617	1.95	-134,438	2.76

Table 3-1 Continued												
	2020		2030		2040		2050		2060		2070	
County	Shortage	V	Shortage	V	Shortage	V	Shortage	V	Shortage	V	Shortage	V
Uvalde	-30,747	0.81	-28,756	0.75	-26,657	0.69	-24,815	0.64	-23,135	0.59	-21,744	0.51
Webb	-4,294	0.21	-2,204	0.15	-2,387	0.15	-10,181	0.32	-17,998	0.48	-25,450	0.58
Willacy	-49,376	1.24	-49,445	1.21	-49,529	1.19	-49,627	1.18	-50,075	1.18	-49,994	1.07
Williamson	No data	No data	No data	No data	-67,836	1.60	No data	No data	No data	No data	-163,807	3.34
Wilson	0	0.11	-8	0.10	-405	0.10	-770	0.11	-1,124	0.11	-1,796	0.11
Wise	-2,300	0.16	-4,261	0.20	-7,926	0.27	-14,772	0.42	-22,099	0.57	-30,339	0.68
Zapata	-1,786	0.15	-1,948	0.14	-2,189	0.14	-2,502	0.15	-2,939	0.15	-3,589	0.15
Zavala	-18,487	0.53	-16,805	0.48	-14,980	0.43	-13,049	0.38	-11,193	0.33	-9,443	0.26

Table 3-2

Data derived from http://www.usclimatedata.com/

Climate by County

Scale Value (V) = $10(S_{MAX} - S)/(S_{MAX}-S_{MIN})$

County	I-35 Corridor	Reference City	Average Annual High Temperature °F	Scaled Value	Adjusted Scale Value	Average Total Annual	Scaled Value	Data
Atascosa	Yes	Pleasanton	81.2	3.13	6.87	32.09	5.60	1981-2010 normals
Bastrop	Yes	Elgin	79.3	4.40	5.60	34.43	5.14	1981-2010 normals
Bell	Yes	Temple	77.1	5.87	4.13	35.84	4.86	1961-1990 normals
Bexar	Yes	San Antonio	79.8	4.07	5.93	32.91	5.43	1961-1990 normals
Blanco	Yes	Johnson City	78.6	4.87	5.13	33.99	5.22	1981-2010 normals
Bosque	Yes	Near Hill County	77.6	5.53	4.47	37.86	4.46	1981-2010 normals
Brazos County	No	College Station	79.3	4.40	5.60	40.09	4.02	1981-2010 normals
Brooks	Yes	Falfurrias	84.5	0.93	9.07	26.42	6.71	1981-2010 normals
Burnet	Yes	Burnet	77.4	5.67	4.33	32.97	5.42	1981-2010 normals
Caldwell	Yes	Lulling	79.6	4.20	5.80	35.91	4.84	1981-2010 normals
Cameron	Yes	Brownsville	83.7	1.47	8.53	27.37	6.52	1981-2010 normals
Collin	Yes	Lavon	75.8	6.73	3.27	40.52	3.94	1981-2010 normals
Comal	Yes	New Braunfels	78.6	4.87	5.13	33.98	5.22	1981-2010 normals
Cooke	Yes	Gainesville	73.8	8.07	1.93	42.8	3.49	1981-2010 normals
Coryell	Yes	Gatesville	79.8	4.07	5.93	33.45	5.33	1961-1990 normals
Dallas	Yes	Dallas	77.1	5.87	4.13	40.97	3.85	1981-2010 normals
Denton	Yes	Denton	76	6.60	3.40	38.08	4.42	1981-2010 normals
Dimmit	Yes	Carrizo Springs	83.4	1.67	8.33	19.72	8.03	1981-2010 normals
Duval	Yes	Benavides	83.6	1.53	8.47	24.63	7.06	1961-1990 normals
El Paso County	No	El Paso	77.5	5.60	4.40	9.69	10.00	1981-2010 normals
Ellis	Yes	Waxahachie	77.7	5.47	4.53	38.81	4.27	1961-1990 normals
Falls	Yes	Marlin	78.1	5.20	4.80	38.48	4.34	1981-2010 normals
Frio	Yes	Pearsall	83.3	1.73	8.27	24.75	7.04	1981-2010 normals
Galveston County	No	Galveston	76.6	6.20	3.80	43.85	3.28	1961-1990 normals
Gonzales	Yes	Gonzales	79.5	4.27	5.73	34.99	5.03	1981-2010 normals
Grayson	Yes	Sherman	72.6	8.87	1.13	43.62	3.33	1981-2010 normals
Guadalupe	Yes	New Braunfels	78.6	4.87	5.13	33.98	5.22	1981-2010 normals
Hamilton	Yes	Hamilton	76.3	6.40	3.60	28.61	6.28	1961-1990 normals
Harris County	No	Houston	79.7	4.13	5.87	49.58	2.16	1981-2010 normals
Hays	Yes	San Marcos	79.6	4.20	5.80	35.75	4.88	1981-2010 normals
Hidalgo	Yes	McAllen	85.9	0.00	10.00	22.24	7.53	1981-2010 normals
Hill	Yes	Hillsboro	77.6	5.53	4.47	37.86	4.46	1981-2010 normals
Hood	Yes	Granbury	76.5	6.27	3.73	37.6	4.51	1981-2010 normals
Jefferson County	No	Port Arthur	78.4	5.00	5.00	60.55	0.00	1981-2010 normals
Jim Hogg	Yes	Hebbronville	84	1.27	8.73	23.83	7.22	1981-2010 normals
Johnson	Yes	Cleburne	77.2	5.80	4.20	37.6	4.51	1981-2010 normals
Kendall	Yes	Boerne	78.3	5.07	4.93	38.12	4.41	1981-2010 normals
Kenedy	Yes	Sarita	82.8	2.07	7.93	29.14	6.18	1981-2010 normals
La Salle	Yes	Cotulla	84.1	1.20	8.80	25.05	6.98	1981-2010 normals
Lampasas	Yes	Lampasas	76.8	6.07	3.93	31.09	5.79	1961-1990 normals
Limestone	Yes	Mexia	77.3	5.73	4.27	40.35	3.97	1981-2010 normals
Lubbock County	No	Lubbock	74.3	7.73	2.27	19.18	8.13	1981-2010 normals
McLennan	Yes	Waco	77.7	5.47	4.53	36.38	4.75	1981-2010 normals
McMullen	Yes	Tilden	84.1	1.20	8.80	23.91	7.20	1961-1990 normals
Medina	Yes	Hondo	80.3	3.73	6.27	26.23	6.75	1981-2010 normals
Midland County	No	Midland	80	3.93	6.07	14.9	8.98	1981-2010 normals
Milam	Yes	Cameron	79.9	4.00	6.00	35.5	4.93	1961-1990 normals
Montague	Yes	Bowie	74.1	7.87	2.13	35.09	5.01	1981-2010 normals
Navarro	Yes	Corsicana	76.7	6.13	3.87	39.73	4.09	1981-2010 normals
Neuces County	No	Corpus Christi	81.5	2.93	7.07	31.7	5.67	1981-2010 normals
Parker	Yes	Weatherford	74.7	7.47	2.53	35.88	4.85	1981-2010 normals
Potter County	No	Amarillo	70.9	10.00	0.00	20.31	7.91	1981-2010 normals
Somervell	Yes	Glen Rose	78.7	4.80	5.20	34.8	5.06	1961-1990 normals
Starr	Yes	Rio Grande City	85.8	0.07	9.93	22.63	7.46	1981-2010 normals
Tarrant	Yes	Ft. Worth	76.7	6.13	3.87	40.97	3.85	1981-2010 normals
Taylor County	No	Abilene	76.2	8.64	1.36	24.83	7.55	1981-2010 normals
Tom Green County	No	San Angelo	78.3	5.07	4.93	21.22	7.73	1981-2010 normals
Travis	Yes	Austin	79.8	4.07	5.93	34.25	5.17	1981-2010 normals
Uvalde	Yes	Uvalde	81.4	3.00	7.00	23.41	7.30	1981-2010 normals
			S_{MAX} = 85.9 S_{MIN} = 70.9			S_{MAX} = 60.55 S_{MIN} = 9.69		

*Temperature scale value subtracted from 10 in order to invert position of value on scale and allow for standardized comparison with other values.

Table 3-2 Continued								
Data derived from http://www.usclimatedata.com/	**Climate by County** **Scale Value (V) = 10(S_{MAX} - S)/(S_{MAX}-S_{MIN})**							
County	**I-35 Corridor**	**Reference City**	**Average Annual High Temperature °F**	**Scaled Value**	**Adjusted Scale Value so 1=R***	**Average Total Annual Precipitation (inches)**	**Scaled Value**	**Data**
Val Verde County	No	Del Rio	81.8	2.73	7.27	19.52	8.07	1981-2010 normals
Victoria County	No	Victoria	80.7	3.47	6.53	41.22	3.80	1981-2010 normals
Webb	Yes	Laredo	85.1	0.53	9.47	20.15	7.94	1981-2010 normals
Willacy	Yes	Raymondville	85	0.60	9.40	26.05	6.78	1981-2010 normals
Williamson	Yes	Georgetown	78.6	4.87	5.13	37.29	4.57	1981-2010 normals
Wilson	Yes	Floresville	81.5	2.93	7.07	29.02	6.20	1981-2010 normals
Wise	Yes	Decatur	74.8	7.40	2.60	39.84	4.07	1981-2010 normals
Zapata	Yes	Zapata	84.6	0.87	9.13	19.53	8.07	1961-1990 normals
Zavala	Yes	Crystal City	83.3	1.73	8.27	20.62	7.85	1961-1990 normals
			S_{MAX} = 85.9 S_{MIN} = 70.9			S_{MAX} = 60.55 S_{MIN} = 9.69		
*Temperature scale value subtracted from 10 in order to invert position of value on scale and allow for standardized comparison with other values.								

Table 3-3						
Data derived from 2007 Texas State Water Plan	**Aquifer Characteristics** **Scale Value (V) = 10(S_{MAX} - S)/(S_{MAX}-S_{MIN})**					
County	**Region**	**Aquifer**	**Area of Outcrop ($miles^2$)**	**Scale Value**	**Estimated Availability (acft-yr in 2010)**	**Scale Value**
Atascosa	L	Carrizo-Wilcox	11,186	6.54	1,014,753	8.30
Bastrop	K					
Caldwell	L					
Dimmit	L					
Frio	L					
Gonzales	L					
Guadalupe	L					
La Salle	L					
Limestone	G					
McMullen	N					
Milam	G					
Webb	M					
Wilson	L					
Zavala	L					
Bexar	L	Edwards BFZ	1,560	9.52	373,811	9.37
Brooks	N	Gulf Coast	0	10.00	1,825,976	6.94
Cameron	M					
Duval	N					
Hidalgo	M					
Jim Hogg	M					
Kenedy	N					
Starr	M					
Willacy	M					
Zapata	M					
			S_{MAX} = 32,294 S_{MIN} = 0		S_{MAX} = 5,968,260 S_{MIN} = 200	

*County to aquifer correlation based on geographic location and does not account for water transfers or other methods by which an area can obtain water from aquifers outside its boundaries.

*Additional aquifers within Texas but not included in study area are considered to strengthen the data set.

Table 3-3 Continued						
Data derived from 2007 Texas State Water Plan	Aquifer Characteristics Scale Value (V) = 10(S_{MAX} - S)/(S_{MAX}-S_{MIN})					
County	Region	Aquifer	Area of Outcrop (miles^2)	Scale Value	Estimated Availability (acft-yr in 2010)	Scale Value
Blanco	K	Trinity	10,652	6.70	205,799	9.66
Bosque	G					
Burnet	K					
Collin	C					
Cooke	C					
Coryell	G					
Dallas	C					
Denton	C					
Ellis	C					
Falls	G					
Grayson	C					
Hamilton	G					
Hill	G					
Hood	G					
Johnson	G					
Kendall	L					
Lampasas	G					
McLennan	G					
Montague	B					
Navarro	C					
Parker	C					
Somervell	G					
Tarrant	C					
Wise	C					
Bell	G	Trinity/Edwards BFZ	1,560	9.52	373,811	9.37
Comal	L					
Hays	K/L					
Medina	L					
Travis	K					
Uvalde	L					
Williamson	G/K					
			S_{MAX} = 32,294 S_{MIN} = 0		S_{MAX} = 5,968,260 S_{MIN} = 200	
*County to aquifer correlation based on geographic location and does not account for water transfers or other methods by which an area can obtain water from aquifers outside its boundaries.						
*Additional aquifers within Texas but not included in study area are considered to strengthen the data set.						

Table 3-3 Additional Aquifers Outside Study Area						
Data derived from 2007 Texas State Water Plan	Aquifer Characteristics Scale Value (V) = 10(SMAX - S)/(SMAX-SMIN)					
County	Region	Aquifer	Area of Outcrop (miles^2)	Scale Value	Estimated Availability (acft-yr in 2010)	Scale Value
Not in study area		Blaine Aquifer	3,443	8.93	315,183	9.47
		Blossom Aquifer	182	9.94	2,270	10.00
		Bone Spring-Victorio Peak	0	10.00	63,000	9.89
		Brazos River Alluvium Aquifer	0	10.00	99,632	9.83
		Capitan Reef Complex	0	10.00	52,150	9.91
		Dockum Aquifer	3,519	8.91	406,138	9.32
		Edwards-Trinity (High Plains)	0	10.00	4,160	9.99
		Edwards-Trinity (Plateau)	32,294	0.00	572,515	9.04
		Ellenburger-San Saba Aquifer	1,147	9.64	45,672	9.92
		Hickory Aquifer	271	9.92	278,316	9.53
		Hueco-Mesilla Bolsons	0	10.00	183,000	9.69
		Igneous Aquifer	0	10.00	14,600	9.98
		Lipan Aquifer	1,565	9.52	48,535	9.92
		Marathon Aquifer	0	10.00	200	10.00
		Marble Falls Aquifer	0	10.00	22,637	9.96
		Nacatoch Aquifer	889	9.72	10,453	9.98
		Ogallala Aquifer	0	10.00	5,968,260	0.00
		Pecos Valley Aquifer	0	10.00	200,690	9.66
		Queen City Aquifer	7,702	7.62	295,791	9.50
		Rita Blanca Aquifer	0	10.00	5,419	9.99
		Rustler Aquifer	309	9.90	2,492	10.00
		Seymour Aquifer	0	10.00	242,226	9.59
		Sparta Aquifer	1,543	9.52	50,511	9.92
		West Texas Bolsons Aquifer	0	10.00	62,325	9.90
		Woodbine Aquifer	1,557	9.52	37,712	9.94
		Yegua-Jackson Aquifer	0	10.00	24,720	9.96
			S_{MAX} = 32,294 S_{MIN} = 0		S_{MAX} = 5,968,260 S_{MIN} = 200	

*County to aquifer correlation based on geographic location and does not account for water transfers or other methods by which an area can obtain water from aquifers outside its boundaries.

*Additional aquifers within Texas but not included in study area are considered to strengthen the data set.

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